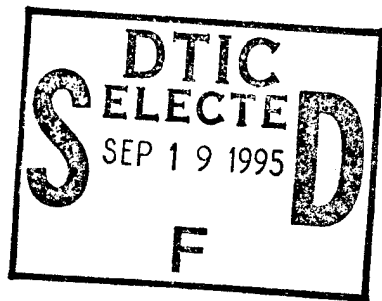


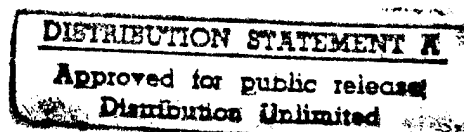
RESOURCE PLANNING AND RESOURCE ALLOCATION  
IN THE CONSTRUCTION INDUSTRY



BY

CHARLES E. MENDOZA

A REPORT PRESENTED TO THE GRADUATE COMMITTEE  
OF THE DEPARTMENT OF CIVIL ENGINEERING IN  
PARTIAL FULFILLMENT OF THE REQUIREMENTS  
FOR THE DEGREE OF MASTERS OF ENGINEERING



UNIVERSITY OF FLORIDA

SUMMER 1995

19950913 030

DTIC QUALITY INSPECTED 5

To my wife, Adelaida, without whose support, love, inspiration and encouragement I would never have written this report. I also would like give special thanks to my parents Juan and Ana Mendoza, my brothers, and sisters for all of their love, and support they provided me throughout my graduate career here at the University of Florida.

Accession For		1
NTIS	CRA&I	<input checked="" type="checkbox"/>
DTIC	TAB	<input type="checkbox"/>
Unannounced		<input type="checkbox"/>
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and/or Special	
A-1		

## ACKNOWLEDGEMENTS

I would like to extend my deep gratitude to Dr. Charles Glagola, my supervisory committee chairman, for his guidance and dedicated support that made this report possible. I am sincerely appreciative of Dr. Zohar Herbsman and Dr. Ralph D. Ellis for serving on my supervisory committee.

## Table of contents

Introduction .....	1
Chapter One - Resource Planning	
1.1 Introduction.....	3
1.2 Human Resources .....	3
1.2.1 Theoretical Personnel Loading Curves.....	4
1.2.2 Practical Personnel Loading Curves.....	6
1.3 Planning the Construction Project Personnel .....	8
1.3.1 Planning Field and Staff Personnel .....	12
1.3.2 Construction Subcontracting .....	13
1.4 Construction Material Resources Planning .....	14
1.4.1 Long Delivery Materials .....	15
1.4.2 Special Materials and Alloys .....	16
1.4.3 Common Materials in Short Supply .....	17
1.4.4 Services and Systems .....	17
1.4.5 Transportation Systems .....	18
1.5 Summary .....	18
Chapter Two - Resource Handling	
2.1 Introduction .....	20
2.2 An Example .....	21
2.3 Limited Resources .....	25
2.4 Resource Leveling .....	26
2.4.1 Single Resource .....	26
2.4.2 Several Resources .....	29
Chapter Three - Resource Leveling	
3.1 Introduction .....	31
3.2 Leveling the Work Force .....	31
3.3 Leveling Procedure .....	32

3.4 Smoothing Resources .....	33
3.4.1 Resource Histograms .....	34
3.4.2 Total Effort and Average Crew Sizes .....	35
3.4.3 Smoothing the Daily Crew Allocations .....	35
3.5 Stretching out a Task .....	39
3.6 The Technique: Steps for Resource Leveling .....	40
3.6.1 Smoothing More than One Resource at a Time .....	41
3.6.2 Checking your Work: Bookeeping Checks .....	41
3.7 Summary .....	43

#### Chapter Four - Resource Constrained Scheduling

4.1 Introduction .....	44
4.2 Heuristics Methods .....	44
4.2.1 An example .....	46
4.2.2 Heuristics Techniques .....	50
4.3 Optimizing Methods .....	52
4.3.1 Mathematical Programing .....	53
4.4 Multi-project Scheduling and Resource Allocation .....	53
4.5 Summary .....	55

#### Chapter Five - Computer Application in Resource Leveling

5.1 Introduction .....	57
5.2 Allocating Resources in Primavera Ver. 1.1a for Windows ....	57
5.2.1 Defining a Resource Plan .....	57
5.2.1.1 Assigning Resources .....	58
5.2.1.2 Driving Resources .....	59
5.2.1.3 Setting Resource Limits .....	60
5.2.1.4 How to Create a Resource Profile .....	61
5.2.1.5 Resource Tables .....	62
5.2.2 Refining the Resource Plan .....	63
5.2.2.1 Adjusting the Resource Distribution .....	63
5.2.2.2 Distribute Resources Non-linearly .....	64
5.2.2.3 Leveling Resources .....	65

5.3 Summary .....	68
Conclusion .....	69
References .....	71
Bibliography .....	74

## INTRODUCTION

Today, construction projects are more complex than ever before. Thousand of tasks must be precisely controlled if a project is to run smoothly, on time, and in budget. The completion of a construction project requires the judicious scheduling and allocation of available resources. Manpower, equipment, and materials are important project resources that require close management attention. The supply and availability of these resources can seldom be taken for granted because of seasonal shortages, labor disputes, equipment breakdowns, competing demands, delayed deliveries, and a host of associated uncertainties. Nevertheless, if time schedules and cost budgets are to be met, the work must be supply with the necessary workers, equipment, and materials when and as they are needed on the job site.

The basic objective of resource planning and resource allocation is to supply and support the field operations so that established time objectives can be met and costs can be kept within the construction budget<sup>1</sup>. It is the responsibility of the project manager to identify and schedule future job needs so that most efficient employment is made of the resources available. The project manager must determine long-range resource requirements for general planning and short term resources for detailed planning. He must establish which resources will be needed, when they must be on site, and the quantities required. The project plan and schedule may have to be modified to accommodate or work around supply problems.

The term resource allocation is used in the case where required resources are assigned such that available resources are not exceeded. Resource leveling is an attempt to project activities in a manner that will improve productivity and efficiency.

This report will present an overview on resource planning and resource leveling. Chapter 1 will describe resource planning and explain theoretical personnel loading curves and practical personnel loading curves, and the planning of the construction project personnel. Chapter 2 will give an introduction on how to handle resources. Chapter 3 will cover resource leveling and indicate how we can level the workforce. Chapter 4 will describe resource constrained scheduling. Chapter 5 will describe the use of computer applications in resource allocation and resource leveling. This chapter will concentrate on how to use the resource leveling in Primavera project planner software application.



## CHAPTER 1 RESOURCE PLANNING

### 1.1 Introduction

Resource planning cannot be accomplished without four essential resources necessary to accomplish the given scope of work: materials, people, equipment, and time. If the project plan and schedule are to be achieved, it is necessary to assure that the required material, labor, and equipment will be available when needed in the required quantities<sup>2</sup>.

Although the resource planning phase is very important, many projects suffer avoidable delays from inadequate resource planning and control. For example, large projects get delays when a certain material is not delivered on time.

In resource planning, we need to identify the quantities of resources required to accomplish the work and schedule these resources over the time of the project.

### 1.2 Human Resources Planning

Human resources for construction planning breaks down into three major categories as follows:

- Home office personnel
- Construction personnel (field supervision and labor)
- Construction subcontractors

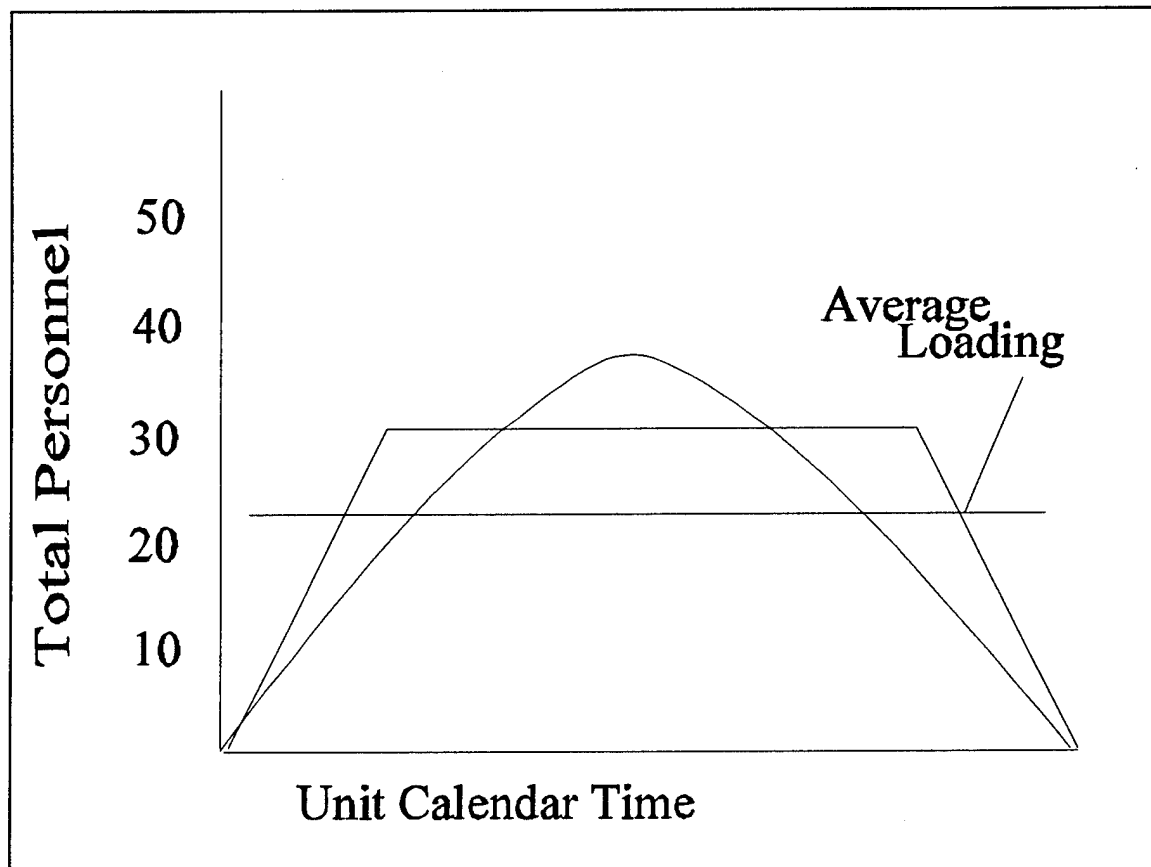
Effectively manning the world's construction projects makes the construction contractor's personnel department a key to successful contracting. Anything the construction managers can do to facilitate staffing their projects such as personnel planning will make their personnel departments' work easier and more effective.

#### 1.2.1 Theoretical Personnel Loading Curves

The simplest form of a personnel loading curves is a trapezoid, as shown in figure 1.1<sup>3</sup>. The curves plot personnel required versus the scheduled time to accomplish the work. Actually the most efficient way to staff a project would be to immediately staff the average number of people required on day one, continue to the end of the work, then drop to zero. The average number of people can be derived by dividing the total hours by the total calendar time, and it is shown graphically by the solid horizontal line in figure 1.1.

We know that such ideal personnel loading is not feasible for many reasons, such as not having the site ready, not having all of the materials and equipment available, and not having enough places for the people to work. Because we have to start from zero and assign people gradually, the next most efficient theoretical personnel loading curve is the trapezoid. It has a uniform buildup, a level peak, and a uniform builddown. In actual practice loading curves take the shape of a bell curve as shown in figure 1.1. Because the bell curve tends to fall inside the trapezoid at the start and the finish, its peak must extend above the peak of the theoretical curve to account for the lost hours. The area under the curve is a value that is set by the total labor hours estimated to perform the work. A

good rule of thumb to remember is that the bell curve peak usually exceeds the average personnel loading curve line by about 20 to 30 percent<sup>4</sup>. This ratio allows you



*Reproduce from: Project Resource Planning*

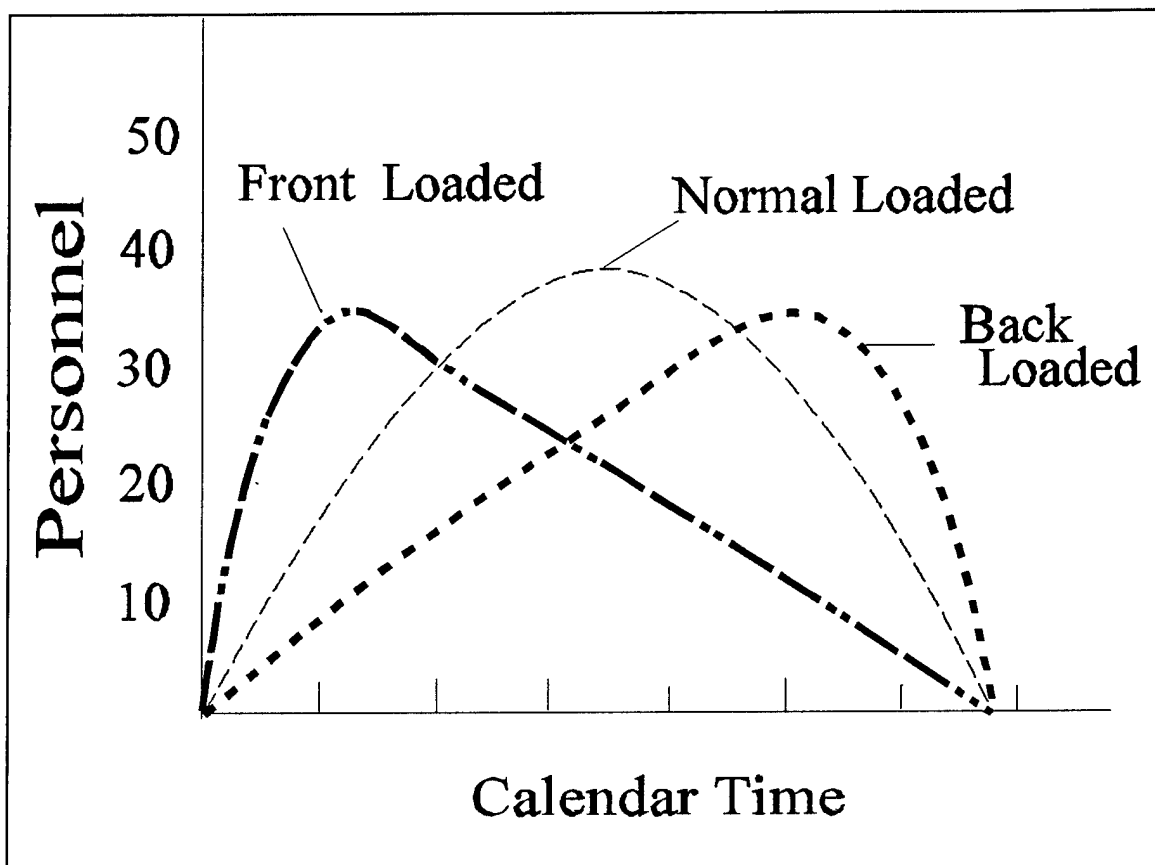
*Figure 1.1 Theoretical Personnel Loading Curve*

to make an approximation of peak craft personnel requirements as soon as the personnel estimate has been completed.

The elapsed time for construction execution runs longer than shown on the theoretical curves, so it's possible to get multiple peaks in certain crafts, as shown in figure 1.4.

### 1.2.2 Practical Personnel Loading Curves

So far, I have discussed theoretical curves, but we need to look at some more likely loading situations that are useful in the practical planning of our human resources. In figure 1.2<sup>5</sup>, I have shown the theoretically ideal bell curve as a dashed line, and the



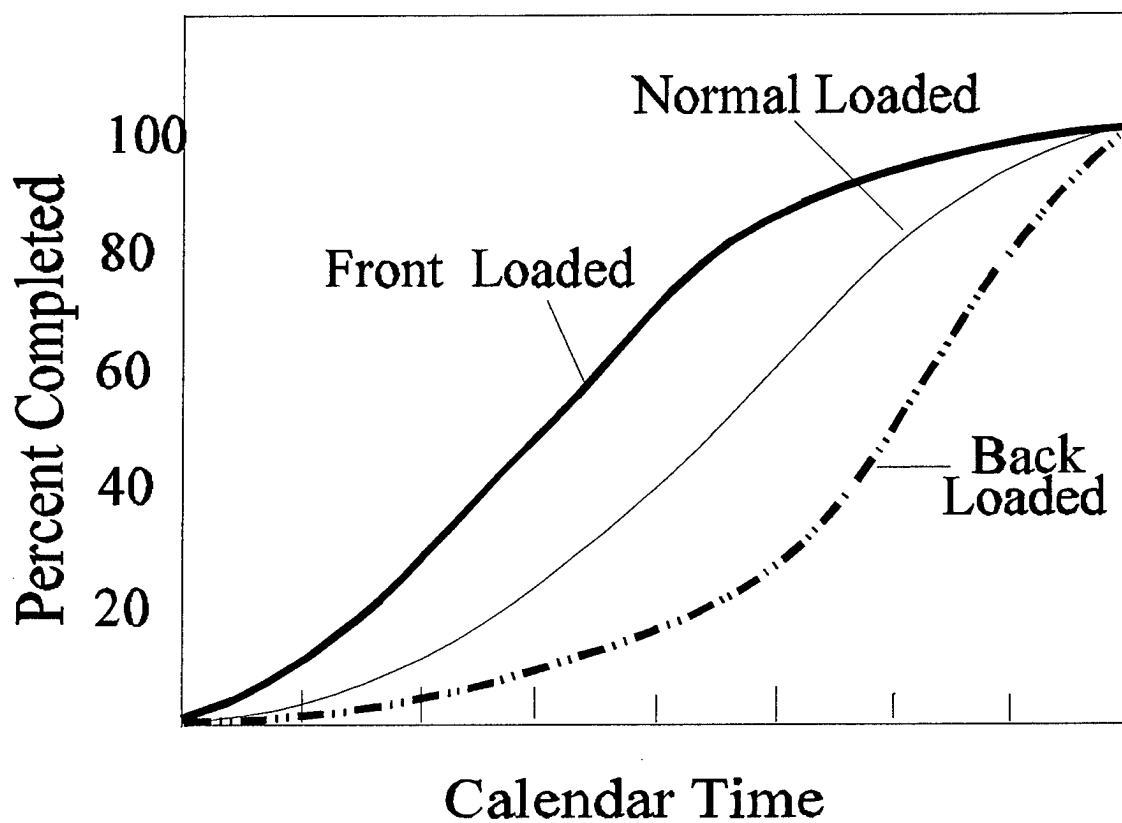
*Reproduce from: Project Resource Planning*

*Figure 1.2 Practical Personnel Loading Curves*

forward and backward loaded curves as other dash lines also. The latter two result when the personnel loading curves occur earlier or later than planned on a project.

The significance of these conditions becomes apparent when we look at the set of "S" curves resulting from plotting percent of hours expended versus scheduled time as shown in figure 1.3.<sup>6</sup>

The "S" curve for the ideally loaded project has a gradual start and finish, which indicates smooth starting and finishing conditions. The forward loaded curve shows a



Reproduce from: *Project Resource Planning*

Figure 1.3 "S" curves from Bell Curves

rapid project start up and an even more gradual than normal phaseout at the end. The backward-loaded project indicates a more relaxed start and a very steep finish slope on the "S" curve. The steep finish leads to such problems as inefficient use of personnel and overrunning the budget. The inefficiency results from having too many people working on only a few remaining tasks.

Normally, personnel cannot be phase off the job so quickly, which means the project will overrun the budget. The simple lesson to be learn here is that front loaded projects may slip to a normally loaded mode and still finish on time. There is little hope that backward-loaded will finish on time. Any slippage during execution further aggravates the phase-out problems and makes the project finish still later and more over the budget than planned.

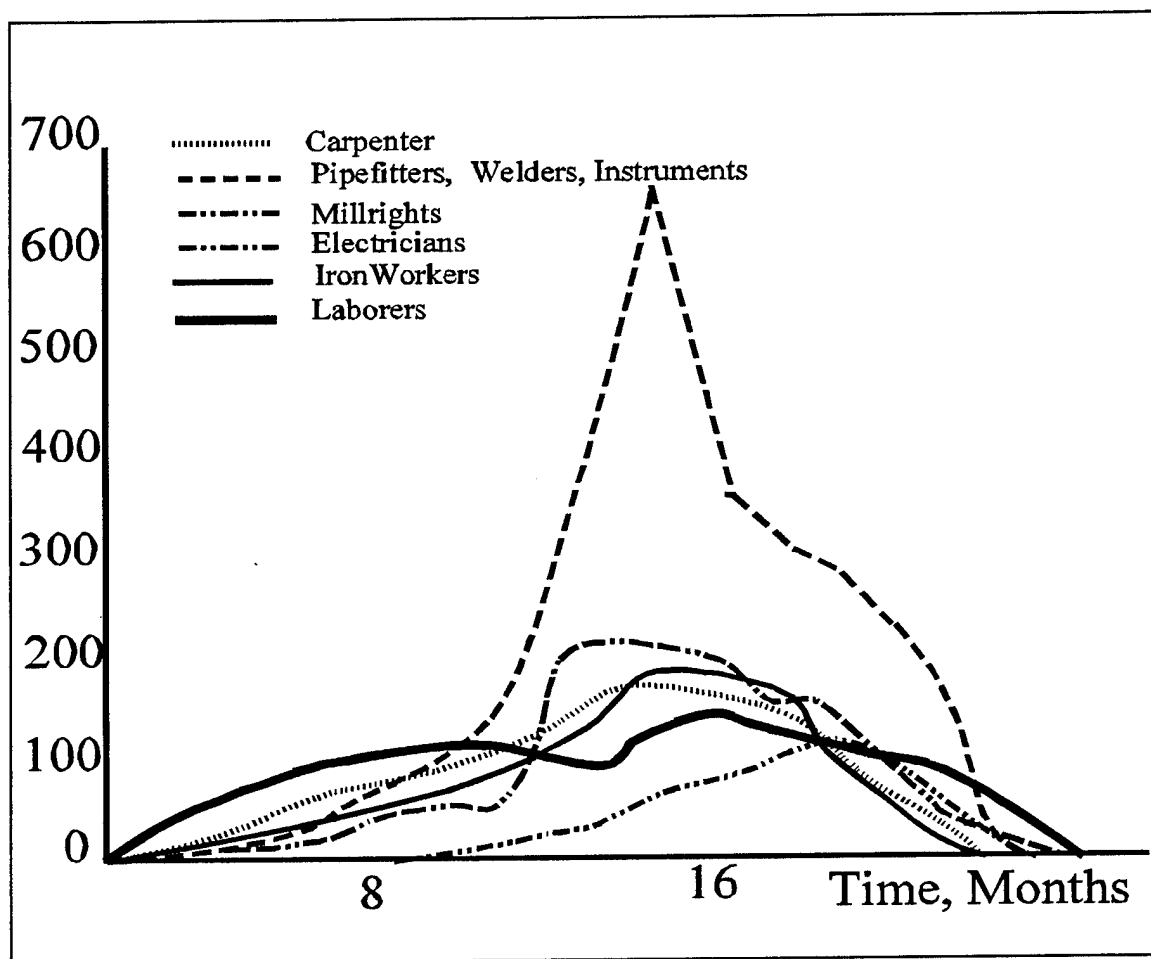
Construction managers must remember, however, that front loaded projects do not happen just by drawing only the personnel loading curves that way. All necessary start-up requirements of design documents, facilities, personnel, and materials and equipment must be available to support an early labor pool.

### 1.3 Planning the Construction Project Personnel

Personnel planning for the field involves detailed craft loading curves and the field supervisory team. When planning for manpower, we should also consider the home office support personnel since they play an important role in the project effort. Because their numbers are usually relatively small, loading curves are not practical. In most projects, the home office personnel are not under the direct administration of the

construction manager. However, it is important to keep track of their project activities if they are charging time to the CM's project budget.

To estimate the total project personnel distribution for the craft labor, it is a good idea to plot a curve for each major craft to be used in the construction. A typical example of such a plot is shown in Figure 1.4<sup>7</sup>, which is actually a composite of all crafts required to build a process type facility.



*Reproduce from: Project Resource Planning*

*Figure 1.4. Construction Labor-Planning Curves*

The basis for making the curves is the number of labor-hours for each craft originally estimated in the construction cost estimate. Each craft supervisor (or the field superintendent) projects the number of people required to carry out the craft's work scheduled for that week. The number of people is obtained by dividing the estimated hours to be expended that week by the hours in the work week. The craft personnel projection can also be done on computer to generate the graph. The weekly value for each craft curve is added to get the composite total craft personnel count. We can see that each craft tends to peak at different times in the schedule, but that the total personnel peaks at about 1430 in about the sixteenth month of the schedule. Peaking in the last third of the project makes this a back-end-loaded project, which is not unusual for a process-oriented project. The main contributors to the late loading are the so-called mechanical trades of pipefitter /instrumentation, millwrights, and electrical, which peak late in the project. That back-end loading on process-type projects is what makes them very difficult to finish on schedule. The nature of the work gives those key crafts a steep build-down curve at the end of the project.

The early availability of the composite craft numbers gives the CM an indication of the type and size of facilities needed for the project as it develops. The "S" curve, which is developed from the total personnel plot, is used by the control people to track the overall construction team's progress during the control phase of the project. The start and finish dates for drawing the curves are derived from the project schedule. Thus we find the so-called building trades of carpenters, laborers, and ironworkers starting early, and



building to a relatively flat peak during the site development, foundation, and steel erection work. Piping shows an early start with a slow buildup during the underground piping phase. Later, piping peaks during the installation of the process and utility instrumentation and piping. Instrumentation and electrical crafts are generally late starters, because they must await the installation of the process and utility equipment, buildings, etc., before they can start their lighting and interconnection work. Their final activity of final system checkout and calibration can be extensive and time consuming in the latter stages of the fieldwork.

The most striking thing about the composite curve is its sharp peak. The sharp peak is a definite cause for concern in a construction labor curve, because it could lead to an overcrowded condition on a limited-access job site just when we are looking for maximum productivity. As we said earlier, the actual curve will tend to roll to the right of the planned curve due to scheduling problems. Unfortunately, that makes a late project finish even more likely. That is a very good reason to consider craft personnel peak-shaving, reducing major peaks by using early start and late finish dates on noncritical activities.<sup>8</sup>

On very large construction projects, the total elapsed time is great enough to have multiple personnel peaks. The longer elapsed time in the construction schedule also gives the possibility of the "roll-to-the right syndrome," making an earlier peak roll over onto a later peak and thereby creating a super peak. That is another reason why using personnel peak-shaving is very critical in planning construction personnel loading curves.

Another factor to consider in the field labor curves is the use of construction subcontractors for a substantial portion of the work. For example, steel for the project may be purchased on a fabricate-and-erect basis, which causes the steel-erection labor to be reflected as a subcontract. If the job involves a large amount of steel work, it may be desirable to include the iron workers in the overall field labor planning chart in fig. 1.4. On the other hand, if the work of a ceramic tile subcontractor is minor, it may not be worth putting in the diagram. The important thing to remember is to account for a high percentage of the total craft labor on the site to give the CM an idea of just how crowded the work site will become.

#### 1.3.1 Planning Field Supervisory and Staff Personnel

The field personnel break down into two groups of people: field supervision and craft labor. Percentage wise, the field supervision labor hours are very low compared to the craft labor hours, so personnel loading curves are not usually required for the supervisory staff. A simple list of the staff and their proposed duration of assignment is usually sufficient. The number and quality of the field supervisory staff are the most vital activities contributing to the success of any construction project.

The number and type of field supervisory staff varies greatly depending on the size, contracting plan, and type of project involved. Table 1.1 shows a range of field supervisory staff numbers and types one might expect to see on various types of projects.<sup>9</sup>

**TABLE 1.1 Typical Sizes of Field Supervisory Staff**

---

Number of People			
Contracting basis	Process	Nonprocess	Types of people
Self-perform (Direct-hire craft labor)	30-50	15-25	Manager, craft supervisors, foremen, administration
Construction Mgmt.. ( All subcontracted)	10-20	5-10	Managers, supervisors, control people
Third party constructor	25-40	12-30	Manager, craft supervisors, foremen, administration

---

*Reproduce from: Project Resource Planning*

The self-perform format means that the contractor is hiring most of the field craft labor directly with a minimum of subcontracting. This results in the largest field staff, because the prime construction contractor furnishes most of the supervisory staff. A construction management approach requires less supervision, because the subcontractors furnish the craft labor and field supervision as parts of their contracts. The construction management firm need only supply the management and administrative personnel to administer and control the field work.

### 1.3.2 Construction Subcontracting

Such trades as insulation, painting, electrical, sheet metal, roofing, etc. normally are subcontracted on most construction jobs. Since the subcontractor has to come to the job site to perform the work, the problems of communications, cost control, and quality

are relatively easy to handle. The prime contractor's field supervisors are available on the job site full-time to oversee the work and to administer the subcontract. The prime contractor's project-control people must supervise the activities of the subcontractors for conformance to schedule, progress payments, and handling change orders.

Most subcontractors are major players on the construction team, so be sure to foster mutual respect and project goal participation among the field staff and the subcontractors. If any subcontractors fail to perform properly, do not hesitate to discuss the problem with their management and to make personnel changes if necessary.<sup>10</sup>

#### 1.4 Construction Material Resources Planning

The basis for construction material resources planning is in the project materials plan. The report resulting from the materials resource plan should include the division of procurement responsibility, current delivery data for engineered equipment, bulk materials, and subcontracts. That's in addition to a survey of current market conditions, pricing trends, bulk materials availability, and vendor lists. Those data are invaluable in formulating the project material resources plan and the project schedule.

In most industrial work, the engineered equipment is purchased by the design firm, because of the lengthy delivery times involved. In that case the constructor is involved only in buying the bulk materials such as concrete, masonry, bulk-piping and electrical materials, and architectural items. Much of the material may also be furnished as part of the work subcontracted to other contractors. It's important that all the required material and equipment needs for the contract be covered in the construction materials

plan. It is vital to project success that the proper equipment and materials be available in time to support the field construction schedule.<sup>11</sup>

Today's materials plan is usually a detailed document listing, by account code, the quantities of the required materials and equipment, a description, their field-required date, responsible supplier, and the like. A computerized spreadsheet or database is ideal for handling the large quantity of information required to control the material on a medium- to large-sized project. The daily update of the materials-tracking document makes computerizing a must.

#### 1.4.1 Long-delivery Materials

Ensuring that the material resources for the project arrive on time involves these important planning areas:

- Long-delivery equipment
- Special materials and alloys
- Common materials in short supply
- Services and system requirements
- Transportation systems

It's very important that the CM make an early review of the project's physical resources to give those items on the critical path special attention. They must be recognized early on to preserve any available schedule float or to keep them from slipping into negative float. It is generally considered that any equipment with a delivery of 10 or more months as potentially long delivery equipment.<sup>12</sup> Delivery times in that area or

longer than 10 months usually place the equipment on the critical path. Examples of long-delivery equipment for industrial projects include such items as sixty-ton air conditioning units, centrifugal compressors, heavy-walled vessels, field-erected boilers, or other complex engineered systems. We cannot assume that we do not have any of those or similar items on your equipment list because almost every project has long-delivery equipment. In most projects, the items with the longest delivery dates are the long-delivery items.

Long-delivery items must be given top priority in the schedule, starting with the first operations in the project design.

#### 1.4.2 Special Materials and Alloys

It is a good idea to review all materials specified for the project that might not normally be stocked because they are of a special nature. Some of these special materials may also require special treatment such as casting, tube-bending, welding, and testing, which tends to delay their delivery even further. Since most CMs are not strong in that highly specialized area, it is best to have your technical staff or consultants thoroughly investigate any potential delivery problem areas. Those long-delivery item reviews should be made early enough that there is still time to deal with the problem. For example, the design might call for a special aggregate in precast wall panels, special window systems, a rare quarried and polished stone, or any one of many others that are likely to fall on the critical path. Early planning for the delivery can get such an item off the critical path, and that can pay a dividend of earlier job completion.<sup>13</sup>

#### 1.4.3 Common Materials in Short Supply

Common materials in short supply often include such ordinarily items as structural steel, concrete, and reinforcing bars. For example, in a large high-rise building, the structural steel will be high in tonnage. Early design and takeoff for placing mill orders for the heavy steel is critical to maintaining the schedule. Each section of the structure must be closely scheduled, if the steel is to be delivered at a time that suits the erection sequence. A large dam project uses huge quantities of reinforcing steel, forms, earth fill, and concrete over long periods of time. These relatively common materials must be planned for and delivered on time if the schedule is to be met. These commonly used materials sometimes tend to be overlooked on larger projects, so do not pass over them lightly. That advice is especially valid if the project is being built in a remote location.

#### 1.4.4. Services and Systems

Strictly speaking, project services and systems are not physical resources, but they must be planned for at about the same time as the physical ones. Planning for them is particularly critical on large projects.<sup>14</sup>

The project scheduling, accounting, cost-control, and administrative systems must be decided on at this time, so that the necessary manual or computerized project-control systems can be effectively implemented. If computers are to be used, the required hardware, software, and communication resources must be planned and implemented. Even such ordinary resources as the office service and the site facilities for construction

have to be planned early. Some items will fall on the critical path some will not, but the critical items must be discovered early to allow for their resolution.

#### 1.4.5 Transportation Systems

Usually this category is involved only on large construction projects that may have an international flavor, either in site location or in purchasing sources. Another special case is construction projects that embody prefabricated modules built off site for erection at remote locations. Any of that type of project will involve special loading, transportation, and receiving facilities to handle unusually large pieces of equipment.

If the project involves a significant amount of foreign or imported equipment and materials, the overall marshaling of shipments, import licenses, custom regulations, dockside security, and invoicing should be developed by the project purchasing manager. The traffic portion of the materials management plan must include all the legal and quasi-legal factors involved in getting the goods to the construction site on time. The CM must review the complete plan to assure that the field construction needs are being fully supported. If the overall system does not function smoothly 100 percent of the time, the field construction operations will be delayed.<sup>15</sup>

#### 1.5 Summary

This chapter wraps up the planning portion of the CM's activities. Effective CMs must train themselves to plan all facets of the project, as well as their day-to-day work activities.



We must remember, however, that a plan is only a proposed baseline for the execution of a project. Any plan is subject to changes along the way. Although it is often necessary to change our plans, it is not recommended making any radical changes to your original plan. If our plans were well thought out, you should resist pressures to change them.

## CHAPTER TWO RESOURCE HANDLING

### 2.1 Introduction

After we considered the timing or schedule of activities and the determination of which activities control the project time, we have to consider questions about the availability or most efficient usage of resources required to undertake the construction operation. It is usually assumed that resources are available in doing the time calculations.

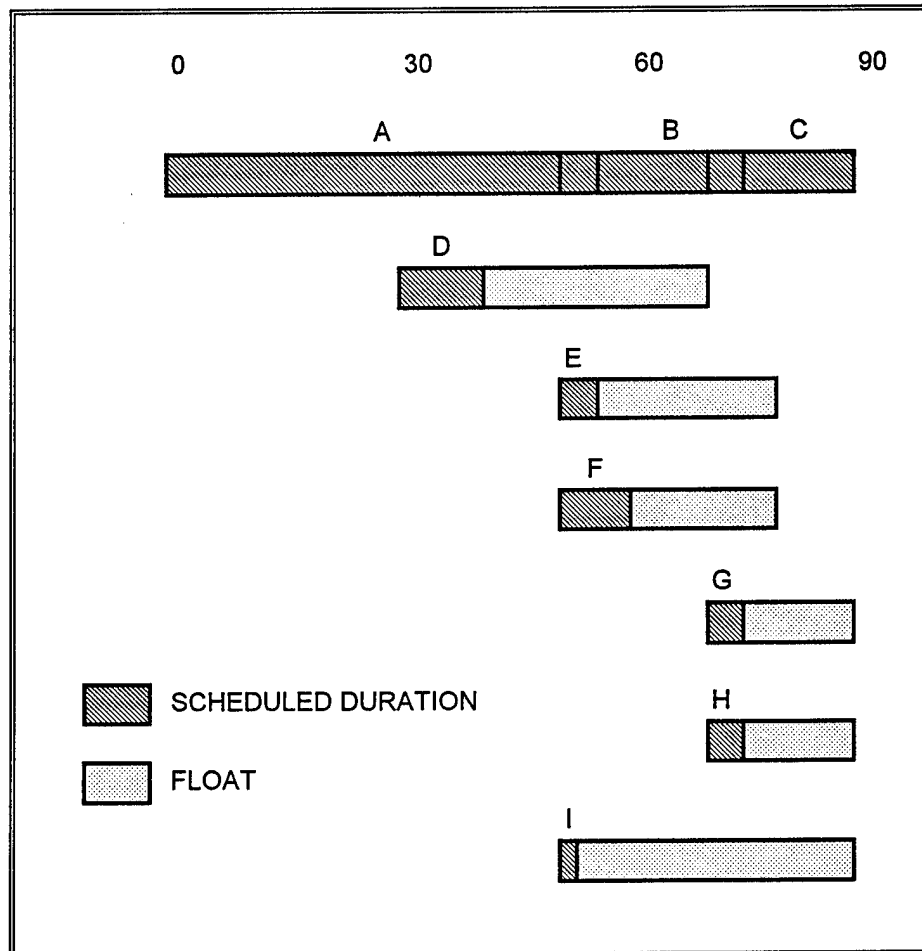
When activities are conducted simultaneously, it leads to simultaneous demands for resources, producing peak resource demands at certain stages of the construction project. Peak demands of resources, particularly over short periods of time, may be undesirable. For example this implies, if workers are the resource, a "hire and fire" situation. As we know, many resources in the construction industry tends to be expensive and limited in number. Skilled labor is often difficult to obtain and costly to fire. Resources not used effectively on site waste money.<sup>16</sup>

Generally, it is more desirable to have approximately uniform resource requirements. This means rescheduling certain activities such that resource requirements are modified. The means for doing this rescheduling are to utilize the available float in the network. A resource use graph or resource profile which is a plot of resource requirements versus time, is found useful for regulating the resource demands. The ideal situation would be to have a level resource use graph or a graph with a few changes in level as possible.

Two distinct types of activities can be identified and can be termed intermittent activities and continuous activities <sup>17</sup>. With the former it is possible to break its operation and restart at a later date. Resources associated with such activities are easier to handle in the resource scheduling exercise than those associated with continuous activities. Continuous activities, once started, must be carried on until completed. When beginning a resource scheduling exercise, the engineer should be aware of the intermittent or continuous nature of the project activities.

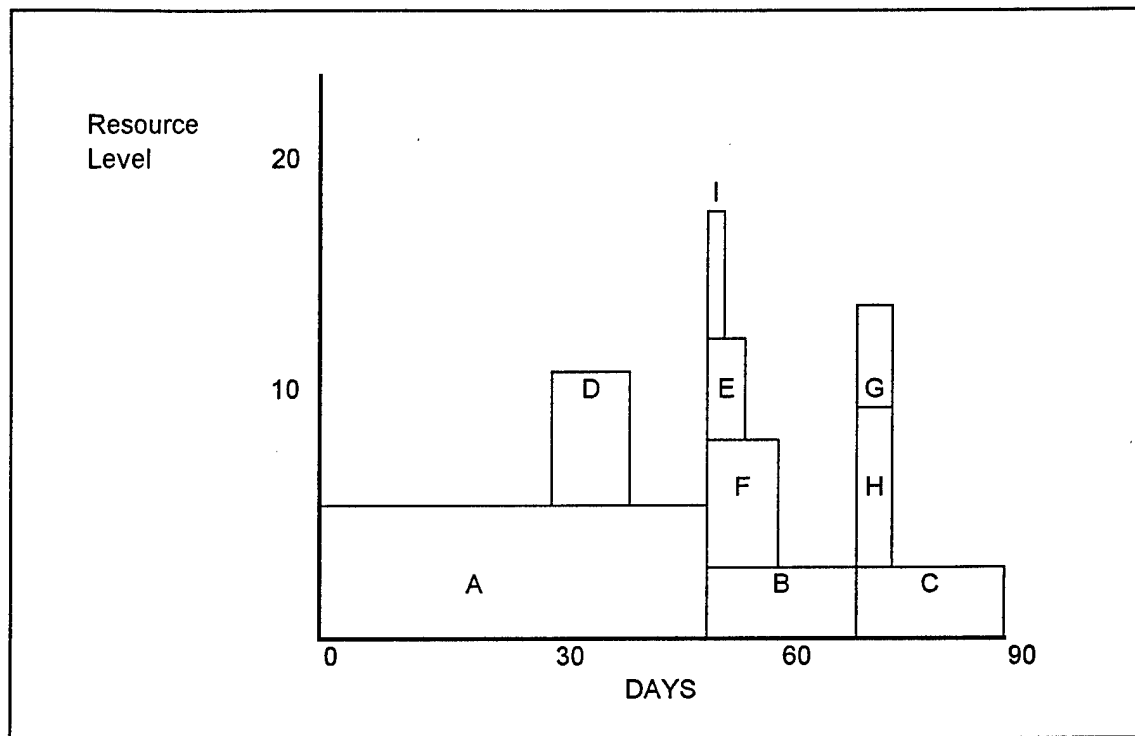
## 2.2 An Example

The bar chart in figure 2.1.a<sup>18</sup> and the activity information in Table 2.1<sup>19</sup> for a small project can be used to plot the resource-use graph of figure 2.1.b<sup>20</sup>. The bar chart is drawn for normal activity durations and for activities starting at their earliest date. The resource, for example, could be workers. The resource usage graph represents the total resource requirements for all activities over the project duration. The graph demonstrates the peak resource demand at certain stages of the construction project. Generally the more uniform the resource demand the better. Once all the available float has been used up, then the only recourse is to extend the total project time if further resource levelling or redistribution is required. In all cases, the starting point is the network calculation based on normal times. These calculations are done assuming availability of resources.



*Figure 2.1.a Small Project Bar Chart*

*Reproduce from : Construction Engineering Network*



*Figure 2.1.b Resource Profile*

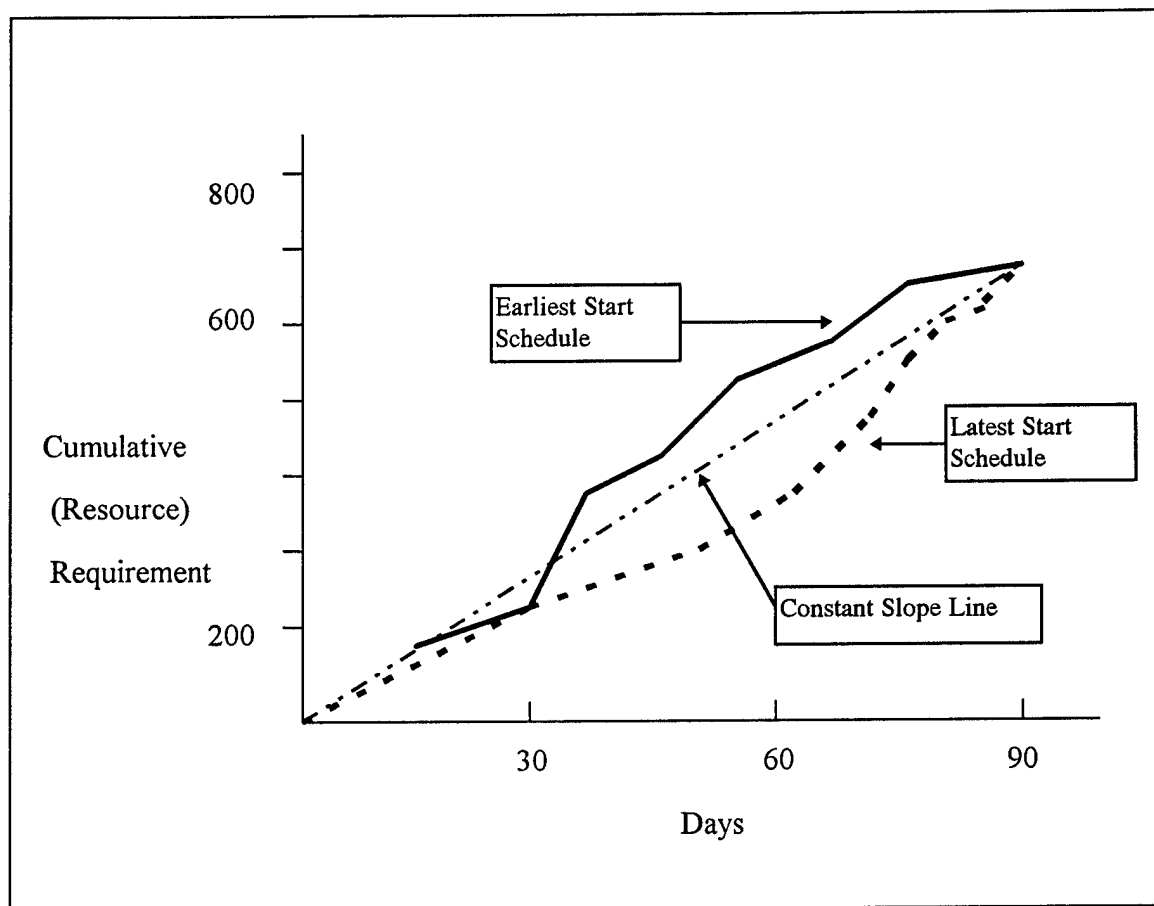
*Reproduce from : Construction Engineering Network*

Activity	Dur	EST	LST	EFT	LFT	TF	Resource Requirements (/ Day)
A	50	0	0	50	50	0	7
B	20	50	50	70	70	0	4
C	20	70	70	90	90	0	4
D	10	30	60	40	70	30	6
E	5	50	75	55	80	25	4
F	10	50	70	60	80	20	6
G	3	70	87	73	90	17	4
H	4	70	86	74	90	16	7
I	2	50	88	52	90	38	6

*Table 2.1 Activity information for example*

*Reproduce from : Construction Engineering Network*

In place of plotting the resource requirements versus the time, the cumulative resource requirements may be plotted. Figure 2.2 indicates the shape that such plots take. Two plots are given: one corresponding to the activities starting as early as possible, the other corresponding to the activities starting as late as possible<sup>21</sup>. The region between the two plots is where the final solution will and often lie. The straight line, from project start to project completion, corresponds to uniform resource usage.



**Figure 2.2 Cumulative Resource Plot**

Reproduce from : Construction Engineering Network

For this example, letting workers be the resource, in a 90 day period the total worker-days required are 702. This gives a uniform daily demand of workers of  $702/90 = 8$  workers.

### 2.3 Limited Resources

Where equipment, labor or materials (or capital) are restricted, the activities have to be rescheduled to satisfy this form of constraint. Frequently this will imply scheduling those activities that use such resources, in a sequential or serial fashion. And this might create the situation where activities overrun their allowable float. This overrun situation may also lead to an increased project completion time and the formation of a different critical path.

If resource limitations are known at the start, for example, only one site crane is available, then the original network plan for the project can include this constraint. In particular this constraint determines which activities may be carried out concurrently and which activities must wait for other activities to finish (that is activity dependence).

In certain cases it may be possible to hire additional equipment to cover peak requirements; in this case no rescheduling of the activities is called for.

As an example of a limited resource, assume that in the previous example only 10 units of the resource were available for the project. Clearly from figure 2.1.b, this constraint is violated on a number of days. The means for resolving problems of limited resources are similar to those for the problem in leveling and their discussion is consequently carried over until leveling is treated.

One possible heuristic for allocating resources is as follows.

- For those activities whose earliest start times are the project start time, assign the resource first to that activity with the least total float and then in order increasing total float. This process may be terminated if all available resources are used up or all activities have their requirements.
- Should all the resources be used up in the first step, the earliest times of the remaining activities (yet to receive resource allocation) are increased. Modify the subsequent parts of the network calculations accordingly.
- For those activities whose earliest start times correspond to when the resources are next available, repeat first step.

## 2.4 Resource Leveling

There are major advantages involved in resource leveling, that is in reducing peak demands for resources and creating a requirement for resources at other non-peak times. In particular with regard to labour or plant, continuity in the workforce, in the recruitment of labour and in the hiring or purchasing of plant are all desirable goals.

There are numerous approaches to the task of resource leveling. Some are described below. There appears to be no one approach that has the consensus of engineers using network programming. The case for a single resource is given first, followed by that for multiple resources.

### 2.4.1 Single Resource

This approach first selects a target maximum for a resource (for example a painting crew of 2 or 3 painters), and proceeds in time, that is from left to right in the resource requirements versus time plot. Where this target level is exceeded, activities contributing to this peak resource requirement are moved into their float time in such a fashion that the peak requirement is removed or shifted. The activity duration may be located anywhere within the interval bounded by that activity's EST and LFT.



There is no definitive rule as to which activities should be shifted. In one approach those activities with the most float (preferably free float) are moved first in this trial-and-error process, as these activities offer the most prospect for relocating the activity to where total resource requirements are at or below the target level. Critical activities remain untouched. Other approaches give first priority for being moved to activities with the first-occurring latest start times and activities with the longest durations. Small projects can often have their resources leveled by inspection.

On one pass through the resource plot, having relocated the starting times of certain of the activities, should the target level still be exceeded, it may be necessary to raise the target level and a second run made through the resource plot.

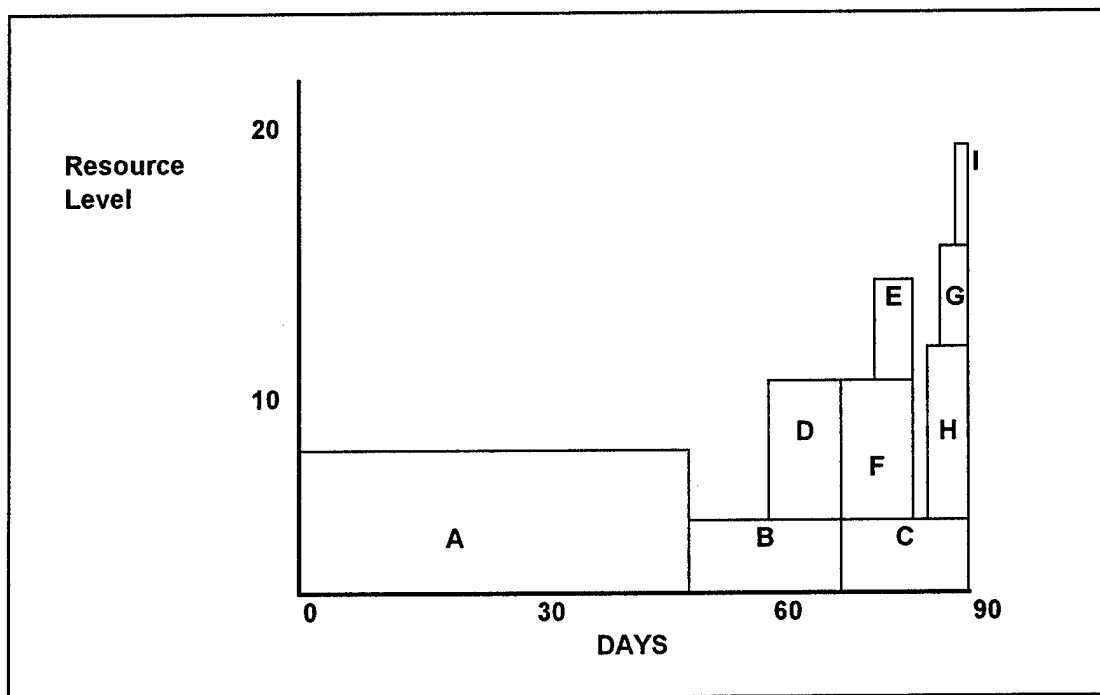
Example<sup>22</sup>: For the example of Section 2.2, following priority rules of moving first the activities with (i) the smallest total float or free float, (ii) the earliest LST or (iii) the longest duration, the activities would be rescheduled, respectively, according to:

- (i) Shift the starting dates of the activities in the following order: H, G, F, E, D, I
- (ii) Shift the starting dates of the activities in the following order: D, F, E, H, G, I.
- (iii) Shift the starting dates of the activities in the following order: F or D, E, H G, and I. Some second priority rule would be necessary to distinguish between moving F or D first.

The application of any one priority rule may not give the best leveled resource solution and a combination of the priority rules coupled with inspection may be needed to give the best solution. For example and by inspection, a reasonable start to the leveling problem would shift activity D to a starting date of day 60, followed by moving the other noncritical activities. Often a lot of juggling of the activity starting dates is required before a suitable resource profile is obtained.

An alternative approach uses a resource plot based on activity start times corresponding to their latest start times (LST). This provides a bound on the activity

schedule as does a resource plot based on activity start times corresponding to their earliest start times (EST). For example Figure 2.3<sup>23</sup> gives the equivalent information to Figure 2.1.b but is based on activity LST as start times. The resource levelling exercise now involves a juggling of the activities between these two limiting cases. Note that with activities scheduled to start at their latest start times, all activities become critical activities. Hence the final solution should preferably be closer to the other bound in order to maintain a certain degree of flexibility in the execution of the activities.



*Figure 2.3 LST Resource Profile*

*Reproduce from : Construction Engineering Network*

#### 2.4.2 Several Resources

Where the resource leveling exercise is to be carried out on several resources simultaneously, again there are several approaches.

In one approach, the exercise is first carried out on the largest fluctuating resource and so on down to the least fluctuating resource. This process may have to be repeated several times, hopefully converging on a final solution.

In another approach, the resource which incurs the largest penalty, should it fluctuate, is treated first. By implication the most costly resource is leveled first. In another approach, first preference in resource leveling is given to equipment, particularly the high cost items, and second preference is aimed at maintaining a reasonably constant labour force. Whichever technique is used, there will generally be the inevitable conflict involved in trying to satisfy all resource constraints simultaneously. There is no real solution to this dilemma. There is no formal algorithm that covers the full spectrum of problems that are encountered in the resource scheduling problem. Some heuristic approaches do exist, however, that tackle parts of the resource scheduling problem. The more successful are interactive, with the engineer doing part of the computations.

The overall optimum resource scheduling solution may involve, as well as the approaches above, time compression of certain activities particularly where the critical activities are contributing to the difficulty of leveling resources. This topic is taken up in the following chapter. Note here that optimum implies not only a consideration of the direct costs associated with resources but also the indirect costs associated with the

project. Generally the idea of an optimum is a theoretical artifice and most solutions are considered satisfactory if they are good or feasible. Where the number of activities is of a manageable size, it is possible to use a computer graphics package to manipulate the activities until a satisfactory resource levelled schedule is obtained.<sup>24</sup>

Resource leveling is treated further in Chapter 3 while resource constrained scheduling is treated further in Chapter 4.

## CHAPTER THREE RESOURCE LEVELING

### 3.1 Introduction

Resource leveling is assigning resources to project activities in a manner that will improve productivity and efficiency. In this chapter, we will deal with the labor, but the same approach can be used for allocating other resources such as equipment and money.

Once the network diagram has been analyzed and all of the event times and activity floats established, the scheduling of all projects activities may proceed. It is important to realized, at this stage, that the individual activity durations used in the critical path calculations imply a commitment to working each activity with sufficient resources to ensure compatibility between the work volume involved in the activity and the productivity and production rate achievable by these resources.

When developing the most up-to-date schedule, we are assuming that we had an unlimited supply of all the resources needed for the tasks, but the real-world situation may be very different. For example, the single crane we budgeted may be needed for two construction tasks at the same time; or the carpentry crew may be required to work on two or more different tasks at the same time; or the carpentry crew may be scheduled for work on two or more overlapping tasks; or the painting crew will not be allowed to work alongside the electricians in a confined space.

### 3.2 Leveling the Work Force

There are four reasons as to why we should level the work force<sup>25</sup>.

1. When the schedule demands more workers per day than are available or if we have workers standing around without jobs, we have a problem.

2. When a new hire is trained, there is loss of productivity. So, if we can keep the trained people and reduce the number of new hires, we should be better off.

3. As we know, every project suffers from start-up problems of some sort. Superintendents and project managers are very busy trying to get every body working in a productivity manner. Therefore, if we can start with a small crew and increase its size gradually, we will eliminate some of the start-up problems.

4. Most projects suffer from congestion around project completion time because of reduced work areas. Thus, if we can gradually reduce the crew size as we approach project completion, we can improve productivity by reducing congestion.

### 3.3 The Leveling Procedure

The goal of any leveling procedure is to schedule all non-critical jobs so that the resource pool is built up step by step to a peak and then allowed to drop off until the pool is exhausted<sup>26</sup>. This is done by:

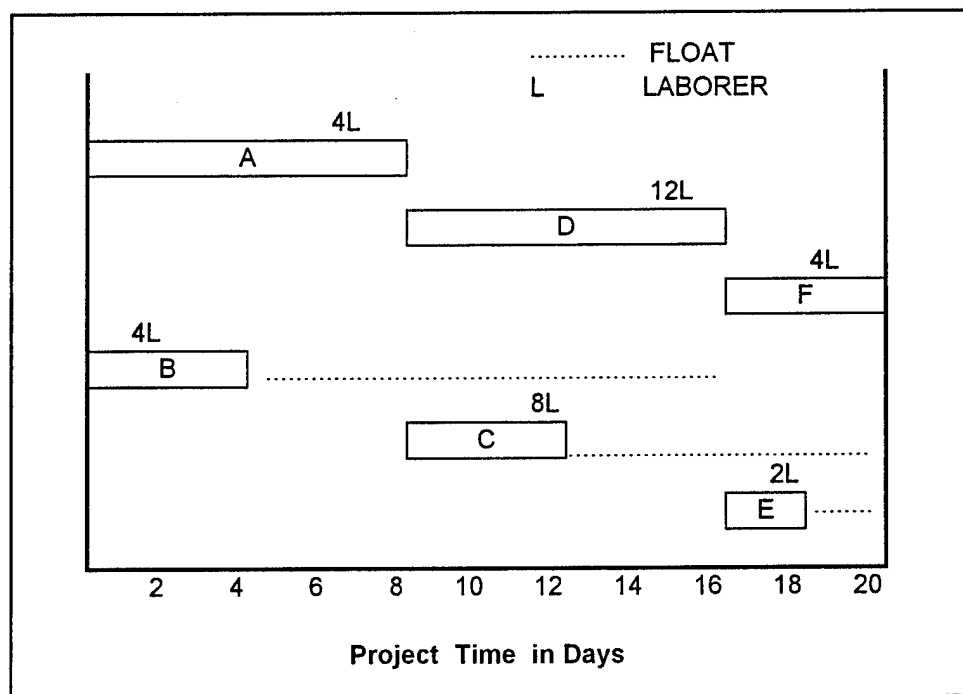
- Scheduling all the critical jobs first.
- Starting the non-critical jobs whenever there is a drop in scheduled manpower up to the point where the peak is reached.
- Starting the non-critical jobs whenever there is a drop so that no ups and downs occur in the resource profile.

The significant factor in leveling is that the starting times for non-critical jobs only are varied to produce a leveled schedule. The project duration is never extended.

### 3.4 Smoothing Resources

One goal of good management is to apply human resources in an effective and efficient manner because on-again, off-again work periods are unsatisfactory to the workers in a crew. We will use an example to illustrate such situations, define the terminology, and explain the graphical aspects.

The basic Gantt Chart for a small project in Figure 3.1 shows when action is



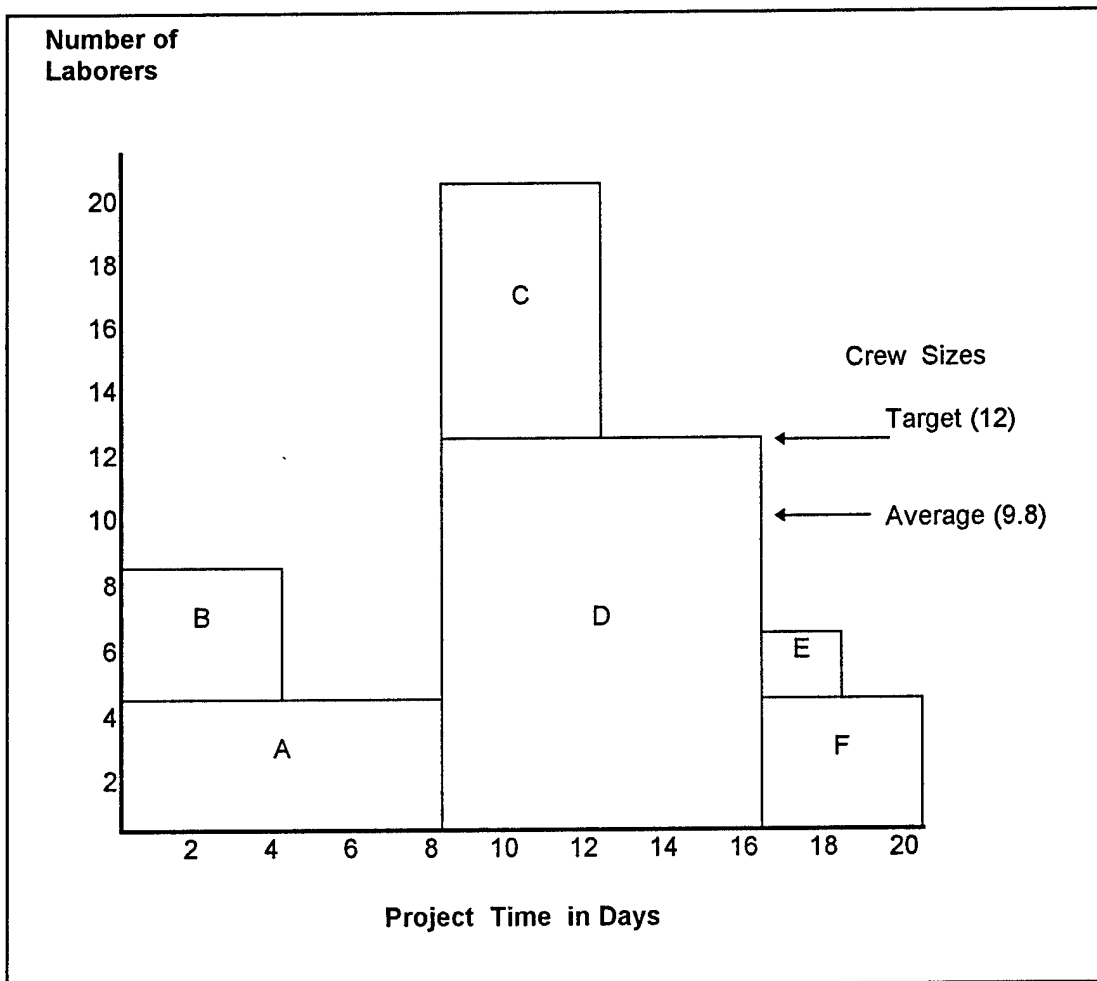
*Figure 3.1 Daily Requirement for Laborers: A Histogram.*

being taken on each task and when specific resources are being used, in this case, laborers.

### 3.4.1 Resource Histograms

The number of workers needed by each task is written in each bar of the chart.

Using this manning data, we can construct a time-based graph showing the total number of workers needed on each day of the project. This is called a resource histogram. A separate histogram is needed for each resource, equipment utilization and labor assignments. The histogram is based on every task starting at its Earliest Start Time and the resource being used for the complete duration of the task. Figure 3.2 is the histogram for laborers.



*Figure 3.2 Daily Requirement for Laborers: A Histogram.*



The total height of a box on the Gantt Chart indicates the total number of workers needed from day to day, obtained by summing the number of workers from each task for that day. It is useful to show the contribution from each task as a separate block on this histogram because this will help later in planning where to relocate a particular task in the histogram.

#### 3.4.2 Total Effort and Average Crew Sizes

A resource histogram provides another function as well: the area inside the graph represents the total number of man-days required for the project. For example, Task "A" needs four workers for 8 days; the effort required is 32 man-days (4 workers x 8 days). Therefore, all the tasks in this small project require a total of 196 man-days over the 20 days of the project, an average of 9.8 workers per day. This gives us a target for smoothing the workforce to less variable levels. Obviously we cannot have half-a-worker so we must be content with a theoretical target of a constant crew of ten workers. After making changes, we must ensure that the total effort is the same as before the changes, 196 man-days.

#### 3.4.3 Smoothing the Daily Crew Allocations

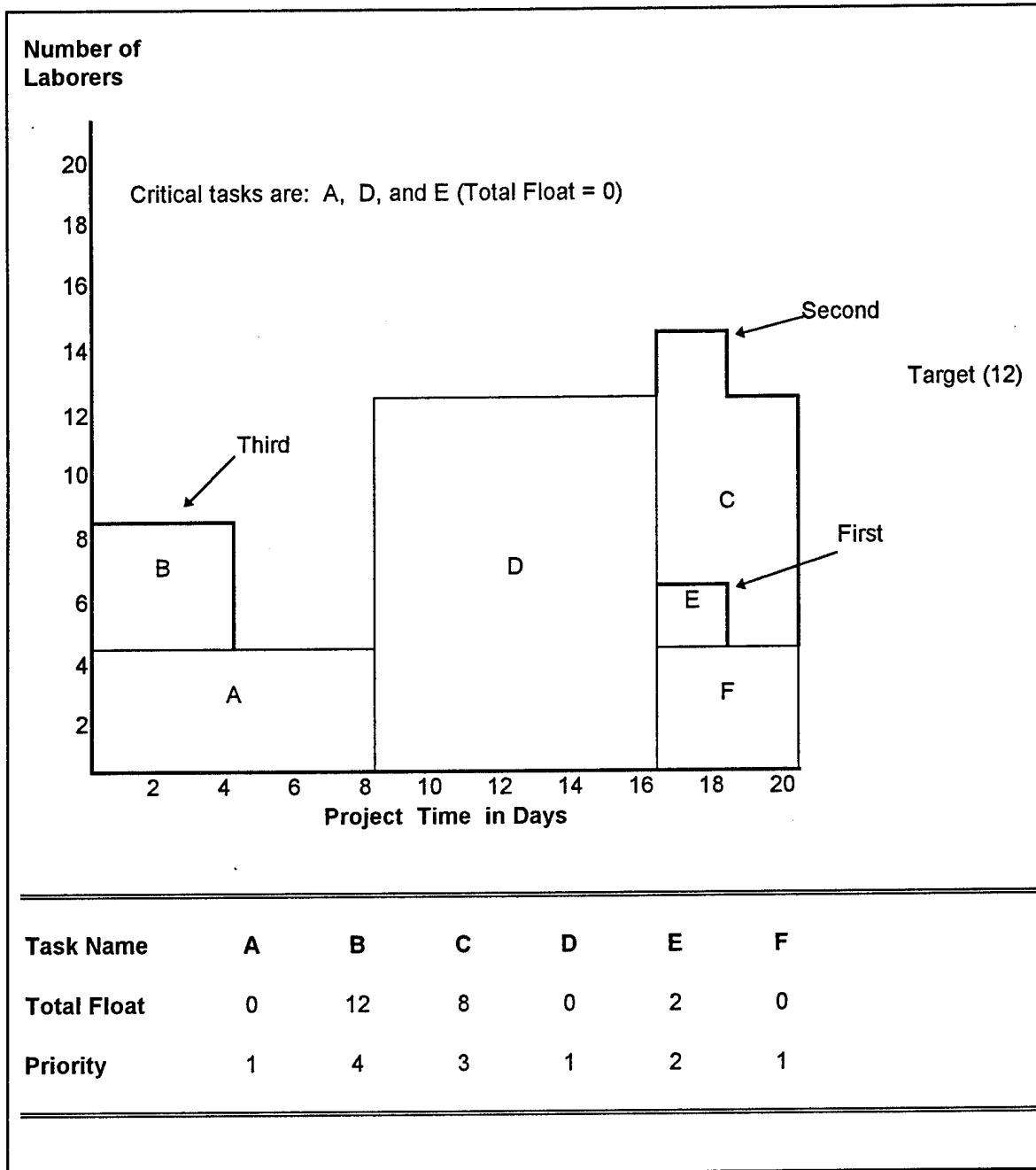
In the example, we should strive to level each day's crew to the ten-person target, but we may have to accept twelve as more realistic. At any rate, the 20 workers scheduled for Days 8 through 12 are unacceptable. To resolve this overload, we need to re-schedule several tasks to start later than their initially calculated Earliest Start Times. We can accomplish this in two stages<sup>27</sup>.

- "Freeze" the critical tasks ( $TF = 0$ ) in their original time periods; then re-schedule the others within their floats, starting with the task having the least float. Note that tasks with  $TF = 0$  have priority ONE. They are "frozen" in time and are scheduled first (that is, in their original time period).
- If the crew size is still too large, re-schedule certain of the critical tasks to minimize the increase in the duration of the project.

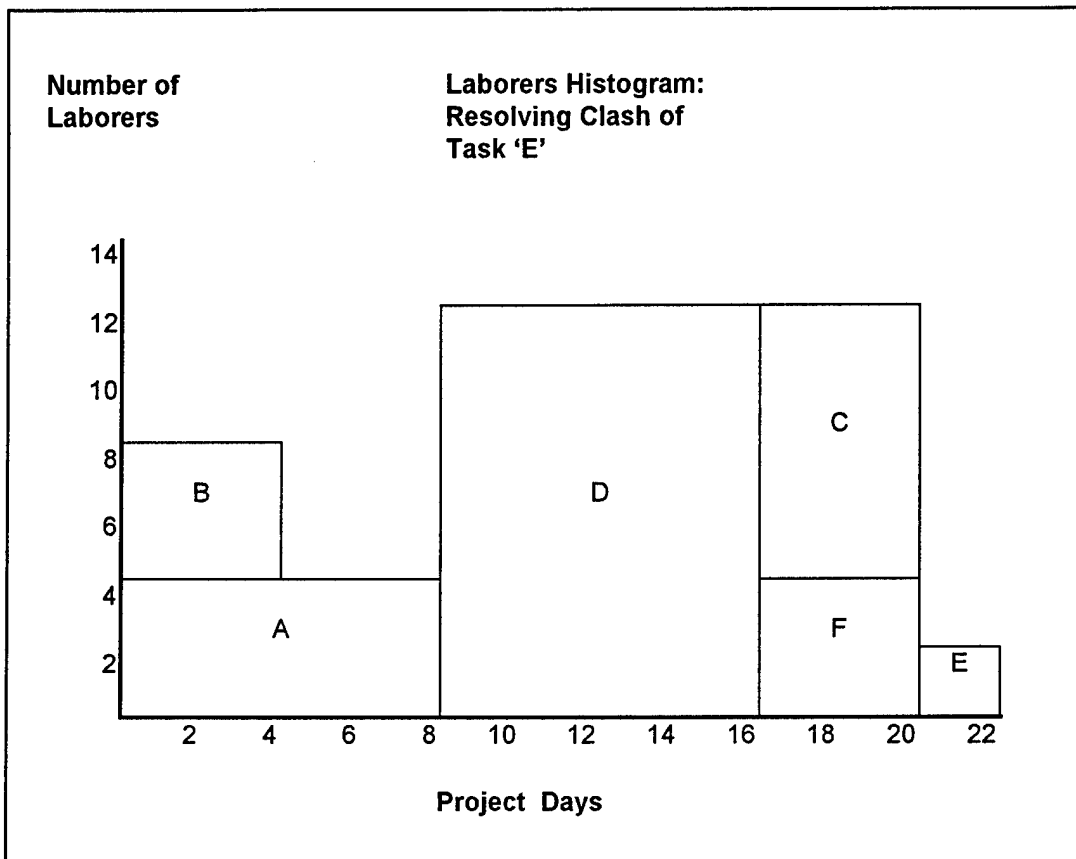
In our example, the priorities based on the Total Floats of the tasks are shown in the table of figure 3.3. The technique works like this: Freeze tasks A, D, and F; then re-schedule E, C, and B. With E left where it is, and C scheduled to start after D is finished, then the original clash of C and D is fixed but a new one is caused between C and E. These changes are displayed in Figure 3.3. Often, a "frozen" task must be moved to a later time slot to preserve the proper sequencing.

One way to satisfy the twelve-man requirement is to start E after F is finished, causing E to become critical and extending the project by two days (see Figure 3.4). In this case, E must be linked to both C and F to ensure that E cannot clash with either one if C or F slips with a longer duration. Alternatively, blindly placing C after F would solve the overload but would lengthen the project by 4 days and cause an irregular crew size.

Projects normally start with a small crew, increase to a maximum near the middle, and then fall off near the end. In this example, we could start Task "B" 4 days late (to start the project "slower") with 4 workers for the first 2 days, followed by a fixed crew of

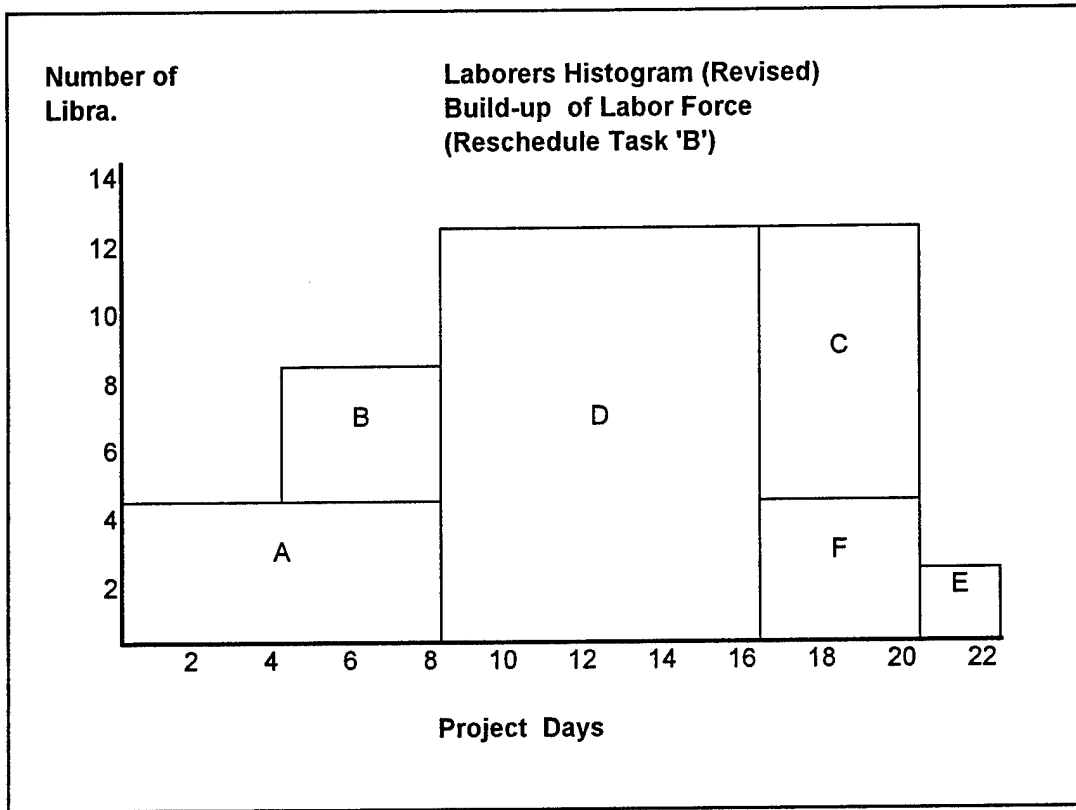


*Figure 3.3 Leveling the Histogram: Stage One*



*Figure 3.4 Resolving the Second Clash*

8 for the rest of the project, ending with two on the last day. This final plan is shown in Figure 3.5.

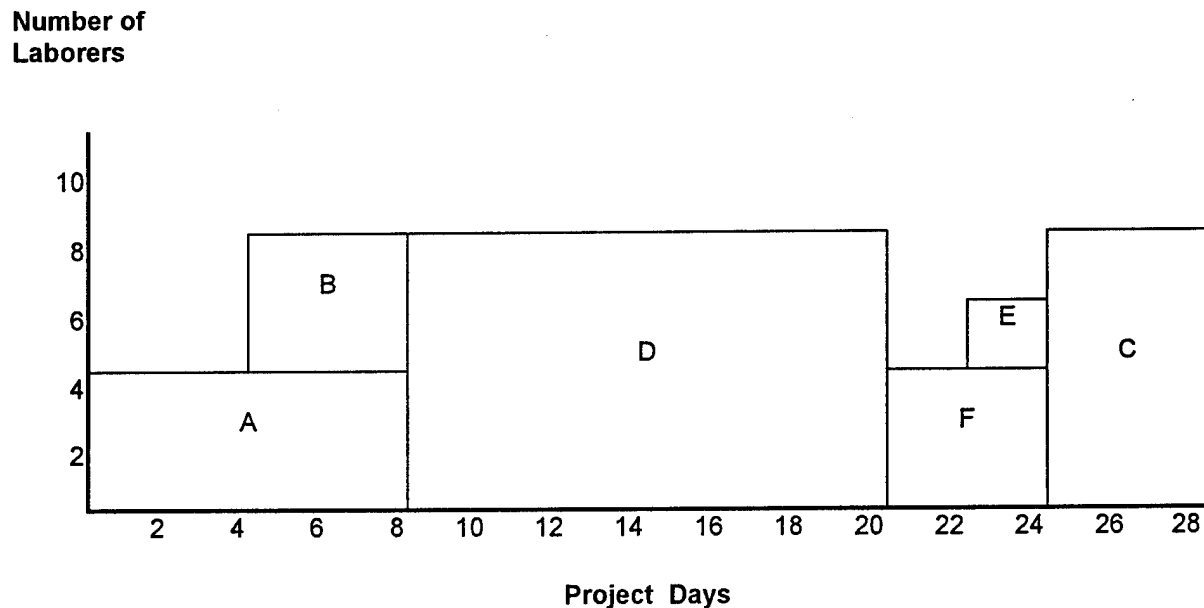


*Figure 3.5 Revised Manpower Loading.*

### 3.5 Stretching out a Task

To lower peaks in the loading and also to fill in the valleys, it may be possible to stretch out a particular task by reducing its crew size and extending its duration<sup>28</sup>. We may be able to tolerate a lower crew efficiency in order to get the benefits of a reasonably constant crew size; each compromise requires that you exercise good judgment. Task "D" requires 96 man-days of effort (12 workers x 8 days), which could be modified to 8

workers for 12 days or 6 workers for 16 days, each of which results in 96 man-days of effort. This stretching technique is useful if an extended project duration is acceptable. The small project we have been using as an example has been stretched; it is shown in Figure 3.6.



*Figure 3.6 Stretching Out a Task*

### 3.6 The Technique: Steps for Resource Leveling

The following are the steps for resource leveling<sup>29</sup>:

- Schedule the task having the EARLIEST Late Start Time (this gives priority to the earliest critical task--for critical tasks,  $LST = EST$ ) and then reschedule the task having the next earliest LST, and so on.
- When several tasks have the same LST, give priority to the one having the smallest Total Float.

- Schedule each task as *early as possible* without violating any of the precedence requirements for the project. When a critical task slips, any task following it must also start later. Refer continually to the network or Precedence Matrix to maintain the order of construction. You can ensure that construction sequencing is not violated by adding links to the network based on the sequencing dictated by your smoothing objectives.
- Ensure that the total amount of each resource scheduled does *not* exceed the prescribed limit; it measures the total effort expended by a crew.

#### 3.6.1 Smoothing More Than One Resource at a Time

This introduction to "smoothing" has focused on smoothing only one resource: laborers. Realistically, there will be more than one type of manpower and equipment that clash among themselves and must be smoothed<sup>30</sup>. Realistic multiple clashes are practically impossible to smooth to their ideal levels because re-scheduling one could cause a clash in another. Compromises must be made. The manager must decide which resource should be "smoother" than the others. If smooth manpower loading is preferable to the smooth use of machinery, then this criterion will guide the re-scheduling of tasks.

#### 3.6.2 Checking Your Work: Bookkeeping Checks Reveal Errors

As we re-schedule a task, its resource bar will be moved along the row and therefore the sums in the bottom row will change; the sum in the last column will not be changed. We must remember to keep track of the effort for each resource each day and

record the totals in the lower rows at the bottom of the page. When we have finished, we can check our accuracy by summing the totals of the last column and comparing it with the sum of values in the bottom row. They should be the same. An example is shown in Figure 3.7, which is based on the small example project described in Figure 3.1.

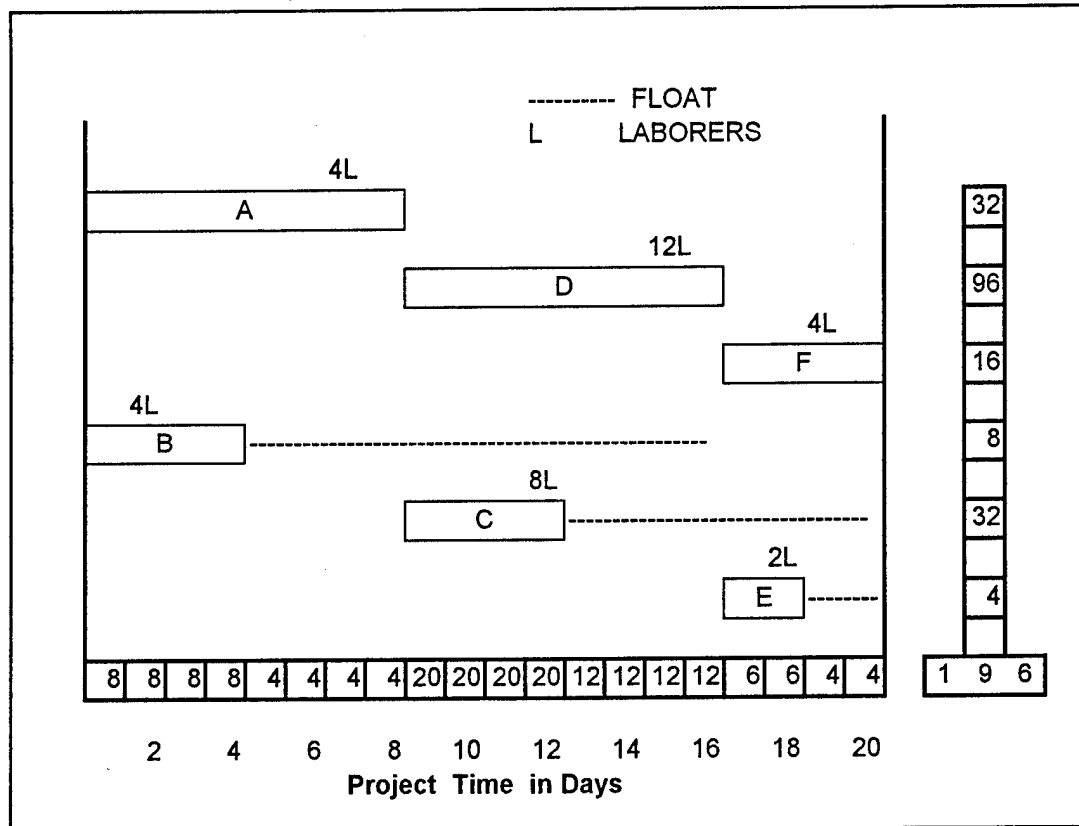


Figure 3.7 Checking the Worksheet

And just as important, the terms in the last column must be the same as they were before you re-scheduled. If not, then you made mistakes. These values in the last row and the last column represent the effort expended for each task on any given day; the total in the lower right corner is the total effort required for the project. This is so because the



fundamental assumption of this method is to reschedule without changing the total resources of any task.

### 3.7 Summary

There is much in this chapter about leveling resources by modifying the schedule of individual construction tasks. We found that the critical tasks could be "frozen" in their original schedule and that the remaining tasks might be re-scheduled within their individual floats. It might become necessary for critical tasks to be re-scheduled, with a resulting extension of the project.

We needed to be careful to ensure that the original precedence requirements were not violated after some tasks were re-scheduled. It is always more challenging to try to level several resources at once rather than only one.

## CHAPTER FOUR

### CONSTRAINED RESOURCE SCHEDULING

#### 4.1 Introduction

The previous chapter examined the process of leveling resources in order to get maximum utilization from the resources. No mention was made of restrictions (constraints) on the availability of resources. However resources are often limited. This tends to require the shifting of activities forward in time until resources are available, leading to a consequent extension of the total project duration.

There are two fundamental approaches to constrained allocation problems: heuristics and optimization models. Heuristic approaches employ rules that have been found to work reasonably well in similar situations. They seek better solutions. Optimization approaches seek the best solutions but are far more limited in their ability to handle complex situations and large problems.

#### 4.2 Heuristic Methods<sup>31</sup>

Heuristic approaches to constrained resource scheduling problems are used for a number of reasons. To begin with, they are the only feasible methods of attacking the large, nonlinear, complex problems that tend to occur in the real world of project management. Second, while the schedules heuristics generate may not be optimal, they are usually quite good. Commercially available computer programs handle large problems and have had considerable use in industry. The heuristic approach attempts to keep the project duration at a minimum while satisfying any resource restrictions, maximizing resource utilization and maintaining resource requirements reasonably level. As discussed

in chapter three, the float of non-critical activities provides the means for shifting activities so as to shift the resource requirements. However, priority rules must be established.

The approach provides a satisfactory solution in reasonable computational time. It also permits the tackling of networks larger than that permitted by any exact mathematical formulation of the problem. It is seen that by allowing activities to be split, extended or compressed, a scheduling better in resource utilization and shorter in duration may be obtained. However, it is recognized that many construction activities do not lend themselves to such modifications.

Most heuristic solution methods start with the CPM schedule and analyze resource usage period by period, resource by resource. In a period when the available supply of a resource has exceeded, the heuristic method examines the tasks in that period and allocates the most scarce resource to them sequentially, according to some priority rule. Some of the more common priority rules are these:

- Select resources with the shortest task first. This rule will maximize the number of tasks that can be completed by a system during some time period.
- Select resources first that require a higher demand on scarce resources.
- Select resources with the minimum slack first. This heuristic orders activities by the amount of slack, least slack going first.
- Select most critical followers tasks. The ones with the greatest number of critical followers go first.

There are many such priority rules employed in scheduling heuristics. Several researchers have conducted tests of the more commonly used schedule priority rules<sup>32</sup>.

Although their findings vary somewhat because of slightly different assumptions, the minimum slack rule was found to be best and almost never caused poor performance. It usually resulted in the minimum amount of project schedule suspension .

One of two events will result as the scheduling heuristic operates . First, the routine runs out of activities before it runs out of the resources, or it runs out of resources before all activities have been scheduled. While it is theoretically possible for the supply of resources to be precisely equal to the demand for such resources, even the most careful planning rarely produces such a neat result. If the former occurs, the excess resources are left idle, assigned elsewhere in the organization as needed during the current period, or applied to future tasks required by the project. If one or more resources are exhausted, however, activities requiring those resources are slowed or delayed until the next period when resources can be reallocated.

If the minimum slack rule is used, resources would be used in critical or nearly critical activities, and delaying those with greater slack. Delay of an activity uses some of its slack, so the activity will have a better chance of receiving resources in the next allocation. Repeated delays move the activity higher and higher on the priority list. We consider later what to do in the potentially catastrophic event that we run out of resources before all critical activities have been scheduled.

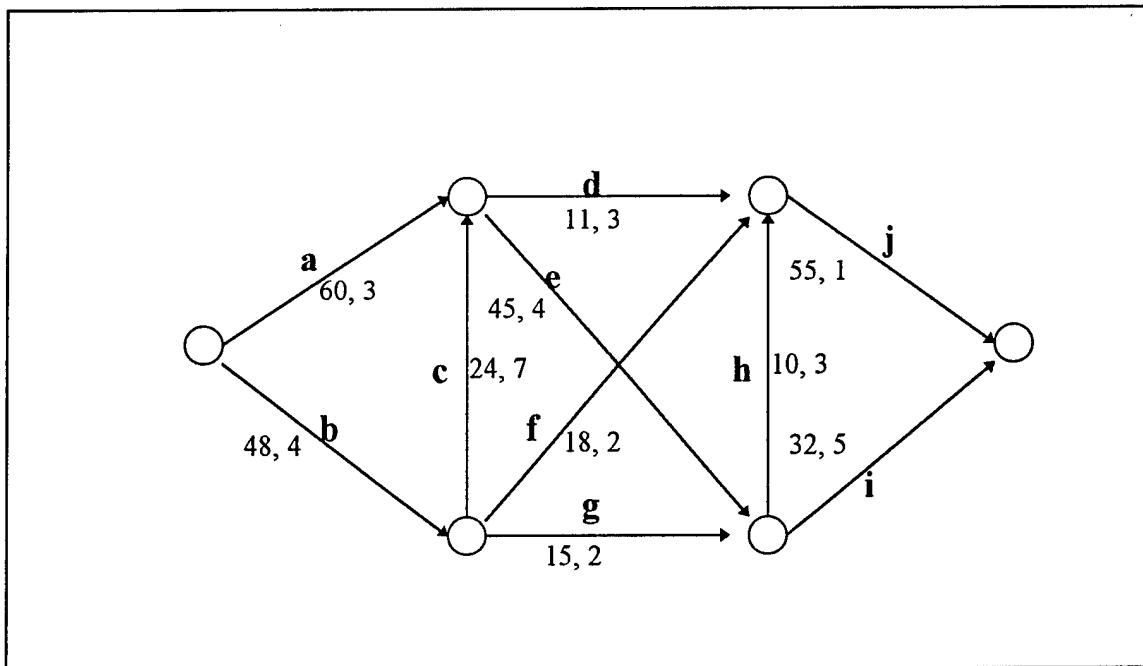
#### 4.2.1 An Example

Consider, for example, the following project scheduling problem.

Given the network and resource demand shown in Figure 4.1, find the best schedule using

a constant crew size. Each day of delay beyond 15 days incurs a penalty of \$2,000.

Workers cost \$200 per day, and machines cost \$100 per day. Workers are interchangeable, as are machines. Task completion times vary directly with the number of workers, and partial work days are acceptable. The critical time for the project is 15 days, given the resource usage shown in Figure 4.1.



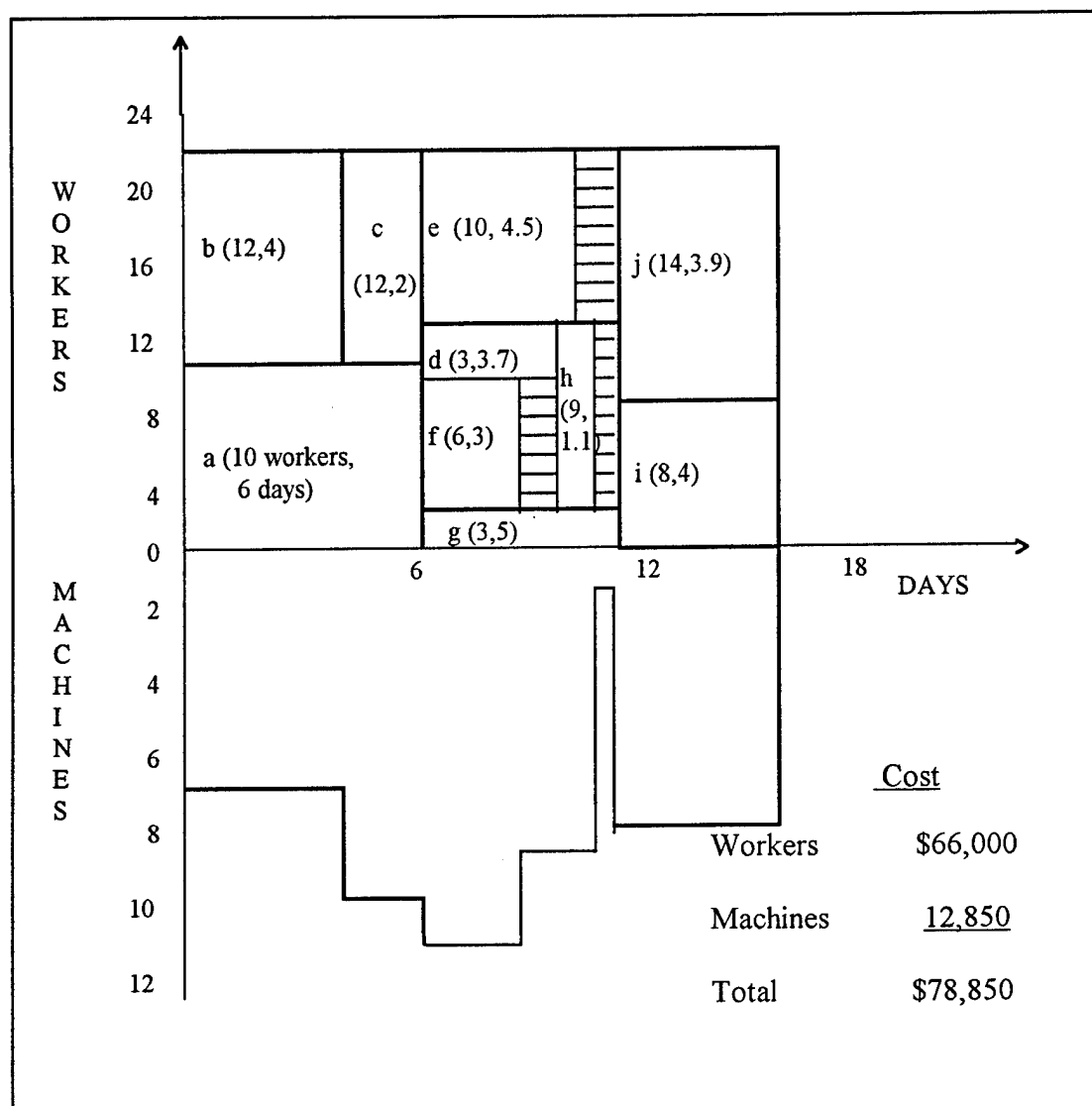
*Reproduce from: Project Management*

*Figure 4.1 Network for Resource Load Simulation<sup>33</sup>.*

*Note: The numbers on the arcs represent, respectively, worker-days, machine-day*

Figure 4.1 lists the total man-days and machines per day normally required by each activity (below the activity arc). Because activity times are proportional to worker input, the critical path is b-c-e-i, and this path uses 149 man-days.

The fact that completion times vary with the number of workers means that activity a could be completed in 6 days with ten workers or in 10 days with six workers. Applying some logic and trying to avoid the penalty, which is far in excess of the cost of additional resources, we can add up the total man-days required on all activities, obtaining 319. Dividing this by the 15 days needed to complete the project results in a requirement of slightly more than twenty-one workers. If we rounded off, it would be twenty-two. How should they be allocated to the activities? Figure 4.2 shows one way, arbitrarily determined. Workers are shown above the "days" axis and machines below. We have 22 workers at \$200 per day for 15 days (\$66,000) and 128.5 machine days at \$100 per day (\$12,850). The total cost of this particular solution is \$45,850. We could remove some manpower from those tasks not on the critical path. If a given activity has slack, we could trade some or all of the slack for a resource saving. Take activity  $j$ , for example. It has 1.2 days of slack. Our basic assumption is that 10 workers can do activity  $j$  in 5.5 days. If we use the slack,  $j$  can take up to 6.7 days without delaying the project. Using this slack, we can reduce the manpower required from 10 to 8.2, saving 1.8 workers for use on a critical task. If the manpower loading on task  $i$  is increased by 1.8 workers, the task time is cut to 3.1 days. It is reduced to  $33/34.8$  or 98.4 percent of its original value. The path b-c-d-j is now critical. Activity slack in other activities can be used in a similar way. If this is not true, the relationship must be known activity by activity, and the amounts of workers/machines that can be shifted subject to the constraints implied by machine flexibility.



*Reproduce from : Project Management*

*Figure 4.2 Load chart for a Simulation Problem<sup>34</sup>*

The purpose of these reassignments is not to decrease labor cost in project. This is fixed by the base technology implied by the worker/mach usage data. The reassignments do, however, shorten the project duration; make the resources available for other work

sooner than expected. If the trade offs are among resources, for instance, trading more manpower for fewer machines or more machines for less material input, the problem is handled the same way.

On small networks with simple interrelationships among the resources, it is not difficult to perform these resource trade-offs by hand. But for networks of a realistic size, a computer is clearly required. If the problem is programmed for computer solution, many different solutions and their associated costs can be calculated. But, as with heuristics, simulation does not guarantee an optimal, or even feasible, solution. It can only test those solutions fed into it.

Another heuristic procedure for leveling resource loads is based on the concept of minimizing the sum of the squares of the resource requirements in each period. That is, the smooth use of a resource over a set of periods will give a smaller sum of squares than the erratic use of the resource that averages out the same amount as the smooth use. This approach, called Burgess's method, was applied by Woodworth and Willie<sup>35</sup> to a multi-project situation involving a number of resources. The method was applied to each resource sequential starting with the most critical resource first.

#### 4.2.2 Heuristics Techniques<sup>36</sup>

Since there are many problems with the analytical formulation of realistic problems, major efforts in attacking the resource-constrained multi-project scheduling problem have centered on heuristics. We mention earlier on some of the common general



criteria used for scheduling heuristics. The most commonly applied rules were discussed in Section 4.2.

Resource Scheduling Method: This give precedence to that activity with the minimum value of  $d$  where

$$d_{ij} = \text{increase in project duration resulting when activity } j \text{ follows activity } i,$$

$$= \text{Max} \left[ 0; (EFT_i - LST_j) \right]$$

where  $EFT_i$  = early finish time of activity  $i$

$LST_j$  = latest start time of activity  $j$

Minimum Late Finish Time: This rule assigns priorities to activities on the basis of activity finish times as determined by CPM. The earliest late finishers are scheduled first.

Greatest Resource Demand: This method assigns priorities on the basis of total resource requirements, with higher priorities given for greater demands on resources.

Project or task priority is calculated as:

$$\text{Priority} = d_j = \sum_{i=1}^m r_{ij}$$

where  $d_j$  = duration of activity  $j$

$r_{ij}$  = per period requirement of resource  $i$  by activity  $j$

$m$  = number of resource types

Resource requirements must be stated in common terms, usually dollars. This heuristic is based on an attempt to give priority to potential resource bottleneck activities.

Greatest Resource Utilization: This rule gives priority to that combination of activities that results in maximum resource utilization or minimum idle resource during each scheduling period. This rule was found to be approximately as effective as the minimum slack rule for multiple project scheduling, where criterion used was project slippage.

Heuristic procedures for resource-constrained multi-project scheduling represent the only practical means for finding workable solutions to the large, complex multi-project problem normally found in the real world.

#### 4.3 Optimizing Methods

The methods to find an optimal solution to the constrained resource scheduling problem fall into two categories: mathematical programming (linear programming for the most part) and enumeration. In the 1960s, the power of LP improved from being able to handle three resources and fifteen activities to four resources and fifty-five activities. But even with this capacity, LP is usually not feasible for reasonably large projects where there may be a dozen resources and thousands of activities.<sup>37</sup> In the late sixties and early seventies, limited enumeration techniques were applied to the constrained resource problem with more success.

#### 4.3.1 Mathematical Programming

Mathematical programming can be used to obtain optimal solutions to certain types of multi-project scheduling problems. These procedures determine when an activity should be scheduled, given resource constraints. It is important to remember that each of the techniques can be applied to the activities in a single project, or to the projects, in a partially or wholly interdependent set of projects. Most models are based on integer programming that formulates the problem using 0-1 variables to indicate whether or not an activity is scheduled in specific periods.

In spite of its ability to generate optimal solutions, mathematical programming has some serious drawbacks when used for resource allocation and multi-project scheduling. As noted earlier, except for the case of small problems, this approach has proved to be extremely difficult and computationally expensive.

#### 4.4. Multi-project Scheduling and Resource Allocation

Scheduling and allocating resources to multiple projects is much more complicated than for the single-project case. The most common approach is to treat the several projects as if they were each elements of a single large project. Another way of attacking the problem is to consider all projects as completely independent. These two approaches lead to different scheduling and allocation outcomes. For either approach, the conceptual basis for scheduling and allocating resources is essentially the same.

When there are several projects, each has its own set of activities, due dates, and resource requirements. In addition, the penalties for not meeting time, cost, and

performance goals for the several projects may differ. Usually, the multi-project problem involves determining how to allocate resources to, and set a completion time for, a new project that is added to an existing set of ongoing projects. This requires the development of an efficient, dynamic multi-project scheduling system.

To describe such a system properly, standards are needed by which to measure scheduling effectiveness. Three important parameters affected by project scheduling are<sup>38</sup>: (1) schedule slippage, (2) resource utilization, and (3) in-process inventory. The organization must select the criterion most appropriate for its situation.

Schedule slippage, often considered the most important of the criteria, occurs when the project is past its due date or delivery date. Slippage can result in paying penalty costs; and this will reduce profits. Further, slippage may caused other projects to slip.

A second measure of effectiveness is resource utilization. This is of particular concern to industrial firms because of the high cost of making resources available. A resource allocation system that smoothes out the peaks and valleys of resource usage is ideal, but it is extremely difficult to attain while maintaining scheduled performance because all the projects in a multi-project organization are competing for the same scarce resources<sup>39</sup>. In particular, it is expensive to change the size of the human resource pool on which the firm draws. While it is relatively easy to measure the costs of excess resource usage required by less than optimal scheduling in an industrial firm, the costs of uncoordinated multi-project scheduling can be high in service-producing firms.

The third standard of effectiveness is the amount of in-process inventory. It concerns the amount of work waiting to be processed because there is a shortage of some

resource(s). Most industrial organizations have a large investment process inventory, which may indicate a lack of efficiency and often represents a major source of expense for the firm. The remedy involves a trade-off between the cost of in-process inventory and the cost of the resources, usually capital equipment, needed to reduce the in-process inventory levels. All these criteria cannot be optimized at the same time. As usual, trade-offs are involved. A firm must decide which criterion is most applicable in any given situation, and then use that criterion to evaluate its various scheduling and resource allocation options.

As noted earlier, experiments by Fendley revealed that the minimum slack-first rule is the best overall priority rule, generally resulting in minimum project slippage, minimum resource idle time, and minimum system occupancy time for the cases he studied<sup>40</sup>. But the most commonly used priority rule is "first come, first served" which has little to be said for it except that it fits the client's idea of what is "fair". In any case, individual firms may find a different rule more effective in their particular circumstances and should evaluate alternative rules by their own performance measures and system objectives.

#### 4.5 Summary

In this chapter, we have shown the two basic approaches to addressing the constrained resources allocation problem.

Heuristic methods which are realistic approaches that may identify feasible solutions to the problem. They essentially use simple priority rules, such as shortest task first, to determine which task should receive resources and which task must wait. Optimizing methods, such as linear programming, find the best allocation of resources to

tasks but are limited in the size of problems they can efficiently solve. Mathematical programming models for multi-project scheduling aim either to minimize total throughput for all projects, minimize the completion time for all projects, or minimize the total lateness for all projects. These models are limited to small problems.

## CHAPTER FIVE

### COMPUTER APPLICATIONS IN RESOURCE LEVELING

#### 5.1 Introduction

The method of resource allocation discussed in the previous two chapters involved simple arithmetic and data manipulation. As one can see, however, that to perform complete resource allocation manually for even an average sized project would be impractical and it would be almost impossible for a large project. Although there are many software applications that do resource leveling such as Primavera, Microsoft Project Manager, Suretrack, etc... , this chapter will be entirely dedicated to Primavera project planner since it is the most common.

#### 5.2 Allocating Resources in Primavera version 1.1 for Windows

This section will give a brief introduction as to how to assign resources , designate driving versus non-driving resources, set resource limits, and check for overloads using on-screen histograms. It will also explain how to refine a resource plan.

##### 5.2.1 Defining a Resource Plan

We define a resource plan by building a list of resources needed to accomplish the project goals and assigning these resources to activities. When assigning resources, we need to decide whether the resource drives the duration of the activity and to check whether the schedule requires more resources than are available by producing resource profiles.<sup>41</sup>

#### 5.2.1.1 Assigning Resources


Here, we need to use the “Resources” form to assign resources to activities. We display the “Resources form” from “the Activity form”; and size and position them so that we can review activity details as we assign resources.

For each resource we need to enter the units per day or budget quantity. If we enter units per day, P3 calculates the quantity to complete by multiplying the amount you enter by the number of days required to complete the activity<sup>42</sup>:

$$\text{Quantity to Complete} = \text{Remaining Duration} \times \text{Units Per Day}$$

At the start of a project, P3 sets the budgeted and forecasted quantities equal to this quantity to complete. If we enter the total budgeted amount for the resource, P3 calculates its rate of use (units per day) as follows<sup>43</sup>:

$$\text{Units Per Day} = \text{Budgeted Quantity} \times \text{Remaining Duration}$$

We can also express resource units as person-days per day, quantities of material to be installed per day (such as linear feet), or any other type of unit. We can assign as many resources per activity as we need. We can simply accomplish this by clicking  on the edit bar in the “Resources” form to add assignments. When we finish, we choose the “OK” button in the Activity form



to save our edits. The “OK” and “Cancel” buttons change to “Previous” and “Next” buttons so we can quickly select the previous or next activity in the table and continue to assign resources.

#### 5.2.1.2 Driving Resources




The duration of an activity sometimes depends on the number of resources assigned to it. In general, the more resources assigned, the less time is required to complete the activity. For example, if a task requires 160 mandays for testing the software, and if we assign 8 person per day, P3 will schedule 20 days to complete the activity. If we were to double the resource amount reduces the task duration to 10 days.

In P3, we can define a resource as "driving," which means that the number of resources assigned to an activity determines its duration. To specify a resource as driving for a specific activity, we check the “Driving” box for that resource. Then, enter the total effort required (budget quantity) and the number of units per time period for the resource. P3 calculates a resource duration, which is used as the activity duration. If we assign more than one driving resource to an activity, the resource that requires the most time to complete determines the original and remaining durations for the activity.

To assign resources we do the following<sup>44</sup>:

1. Choose “Display”, “Activity Form” and click the “Res” (resources) button to open the blank Resources form. Or select an activity and

then choose “Edit”, “Assign Resource” to show only the “Resources” form already in edit.

2. Select an activity by clicking it in the “Activity” table or “Bar” area.
3. Type up to eight characters for the resource name in the Resources form edit bar and click  or press Enter. On the other hand, if we have predefined resource names in the “Resource Dictionary”, click  to display the list of resources. If the resource is new, P3 prompts you to add it to the “Dictionary”.
4. Enter the units per time period or budgeted quantity.
5. Click  in the “Resources” form edit bar to add another resource to the same activity and repeat steps 3 and 4. When you finish, choose “OK” in the “Activity” form or select another activity. P3 will automatically calculate resource quantities.

#### 5.2.1.3 Setting Resource Limits

When we finish allocating resources, we can view histograms on-screen to examine resource distribution across the project. Here, we can tell when resource use is overallocated by first defining availability limits in the “Resource Dictionary”. If we are planning to level resources, we must set limits<sup>45</sup>. To do so, we must choose “Define”, “Resources” to display the “Resource Dictionary”.

To set resource limits, we select a resource from the list and enter values in the normal and maximum columns. The normal limit is the typical availability of

the resource while the maximum is the highest amount of the resource that is available at one time. For example, the carpenter is usually available for 8 hours but he can work up to 10 hours per day.


We can also use P3's on-screen graphics to determine whether resources are sufficient to complete the scheduled work. If a profile shows that some activities need more resources than are available, use P3's leveling feature to redistribute resources across the schedule. We can also expand or compress the timescale of a resource by adjusting the timescale on the Bar chart.

When we click the “Emphasize” overload with colors checkbox, the bar color changes as resource use exceeds the limits. Green bars indicate use within availability, yellow bars mean that resource use exceeds the normal limit but is still within the maximum, and red bars signal usage above the maximum limits of availability. When choosing draw limits, P3 draws a yellow horizontal line across the profile at the normal availability limit, and a red line to define the maximum limit.

#### 5.2.1.4 How to Create a Resource Profile

To create a resource profile, we must do the following<sup>46</sup>:

1. Choose “Display”, “Resource Profile”. P3 displays a profile for the first resource in the “Resource Dictionary”.

2. Click  and choose a resource from the list. Scroll to the bottom of the list and choose "Total" to display a profile for all resources defined for the project.
3. Choose the "Display" button to change options. For example, display units or costs; choose a different time interval; choose whether to show total (combined), peak (highest), or average (total/number of time units in interval) use; and choose whether you want to show bars, curves, or both.
4. Use the "Select" button to choose multiple stacked resources or grouped resources. To stack resources, use different group numbers and colors for each line of resource selection. To group resource usage in one bar, assign the same group number and color to each line of resource selection.

To close the resource profile, choose "Display", "Resource Profile" again.


#### 5.2.1.5 Resource Tables

Resource tables show as listing of resource distribution over time. It summarizes the total number of resources per day, week, month, quarter, or year.

We can specify whether to display peak, total, or average-use values.

To create a resource table, we must do the following<sup>47</sup>:

1. Choose "Display", "Resource Table".

2. Click  and choose a resource from the list. P3 creates and displays a table for all resources, beginning with the resource you selected.
3. Click the “Display” button to modify options.
4. To choose specific resources, click the “Select” button. Assign a unique row number to each line of resource or cost-account selection. One can group resources in the same row by assigning them the same row number. In this case, use the “Group Name” column to define a title for the resource group.

#### 5.2.2 Refining the Resource Plan

We refine the resource plan by reallocating resources or defining specific lags and durations to reflect the actual start and end dates for resource use. If resource use is nonlinear, we can use a resource curve to accurately define resource distribution across the activity. If resources are still overloaded, we can level them.

##### 5.2.2.1 Adjusting the Resource Distribution

When we assign resources in P3, their use starts when an associated activity starts and continues until the activity completes. However, we can use resource lags and durations to control the times resource use begins and ends. A lag is a delay between the start of the activity and the start of the resource use<sup>48</sup>; for example, a resource may not be needed until a few days after an activity begins.



If a resource is not needed throughout an activity, we can specify a resource duration.

#### 5.2.2.2 Distribute Resources Non-linearly

Although we can use resource lags and duration's to define the beginning and end of resource use, by default P3 uses the same number of units each day of the activity. We can describe precisely how we want to distribute resources across an activity by using resource curves. For example, we can allocate most resource use at the beginning of the activity duration using a front-loading curve, or use a back-loading curve to place most resource use at the end. We can use a bell curve when resource use begins slowly, gradually increases as the activity progresses, and tapers off at the finish of the activity.

The "Define", "Resource Curves" command enables us to create up to 16 curves for distributing resource use. P3 provides a standard set of nine curves for all new projects; we can use them as provided, modify them, or add our own.

To create a resource distribution curve, we must do the following<sup>49</sup>:

1. Choose "Define", "Resource Curves" .
2. Click  on the edit bar and enter a resource designator from 1 to 9 or A through F. Enter a description for the curve .
3. Point to the top of a bar. When the mouse pointer changes to  , drag the bar up or down to indicate the percentage of total resource use to

allocate for that percent of activity duration. We can also enter specific values along the bottom row.

4. Choose the "Prorate" button to recalculate the values so they total 100 percent. Choose "OK". Use the "Restore" button to return the curve to its original values before the changes are applied.

Check resource availability once curves are assigned; we may need to change resource distributions to avoid overloads. We can use these curves in conjunction with resource leveling to produce an optimal resource plan.

#### 5.2.2.3 Level Resources

After using resource lags and curves to refine the resource plan, and if profiles show that some activities still need more resources than are available, we can use P3's leveling feature to redistribute critical resources across the schedule. Resource leveling compares the allocation of resources to availability and delays certain activities to remain within these limits. Resource leveling does not change activity durations or resource requirements; it can, however, delay schedule dates.

During leveling, P3 reschedules activities whose combined resource needs exceed the availability limits defined in the "Resource Dictionary". Before an activity can be rescheduled, however, all its predecessors must be completed, and all the necessary resources for the activity must be available for the entire duration of the activity. P3 delays the activity until both requirements are satisfied.

P3 provides several options for resource leveling. We can level the entire project or, if we are only concerned with resource requirements for the next 2 weeks, for example, we can save processing time by leveling only as far as the cutoff date you specify.

We can also specify whether P3 levels forward or backward. P3 normally levels activities according to their early schedule dates, starting with the first activity with no predecessors and continuing to the last activity in the network; this is called forward leveling. P3 can also perform backward leveling, in which activities are leveled using their late schedule dates. In a backward-leveled schedule we can see the latest possible dates for activities without exceeding resource availability. When we backward level, P3 moves activities forward in time, instead of delaying them.

P3 always produces an analysis report that shows the results of leveling resources. When we level a project, we can produce additional reports, such as a tabular schedule, to examine the effects of leveling on the entire schedule.

An additional option enables us to smooth resources based on time or resource constraints. Resource smoothing uses positive float to minimize sharp changes in resource use. During non-time-constrained smoothing, P3 makes several attempts to schedule an activity within the maximum availability limit of the resource, thereby reducing the possibility of delays. When time is more important than resource availability, time-constrained resource smoothing automatically doubles the maximum resource limit in an attempt to schedule the activity without




delays. Choose the “Resources” button to specify the resources that we want to level. Although P3 can level up to 120 resources at a time, we should select the ones that are most critical to our project schedule.

To level resources, we must do the following<sup>50</sup>:

1. Choose “Calculate”, “Level” to level resources for the current project.
2. Click the checkboxes you want to select in the “Resource Leveling” dialog box.
3. Choose the “Resources” button to identify the resources for leveling.

One can only level resources for which normal and maximum availability limits are defined in the Resource Dictionary.

4. Click  to specify a resource in the “Resource Selection” dialog box. Click “OK” when you finish entering resources.
5. Choose “OK” again from the “Resource Leveling” dialog box to start the processing.

Once resources are leveled, the leveled dates replace the current schedule dates for the project. If we calculate the schedule, P3 replaces the leveled dates with the schedule dates without the effects of leveling.

Resource leveling helps us evaluate options; it does not produce optimal solutions. Rather than accept the results of any leveling run at face value, we should consider alternatives.

### 5.3 Summary

Although there are many software applications as well as computer programs that can help us with resource leveling, Primavera project planner is the one software application that most project managers use today. This application has managed to reallocate resources or juggle the schedule to resolve conflict between activities that use the same resources. It also helps us to level our resource plan and examine the resource use to determine whether the plan contains hard to manage peaks and valleys.

## CONCLUSION

The construction industry today is facing more and more challenges than ever before. This includes increased complexity of projects, more costly project and stricter rules and regulations under which to operate. Without the proper resource allocation, one will pay the price for late job completions and cost overruns.

Resource allocation as described in this report must start with a good solid plan. It cannot be accomplished without defining four essential elements which are materials, people, equipment, and time. Therefore, planning is very essential since many projects can suffer unavoidable delays from inadequate resource planning. In the planning phase, we must identify the required resources needed to complete the project.

After we have identified the resources needed to complete the project, we must be able to allocate them in order to undertake the construction operation. When applying resource leveling, we assumed that we have an unlimited supply of resources required for the tasks, but we must remember that the real world situation may be different. The goal of resource leveling is to assign resources to project activities in a manner that will improve productivity and efficiency.

As mentioned before, resources are often limited and this tends to shift the activities forward in time until resources become available. In this report we have presented two ways to approach constrained allocation problems. These were the heuristics and optimization models. The former one identifies feasible solutions to the problem using simple priority rules, such as shortest task first, to determine which task should receive resources and which task must wait. The latter solution finds the best

allocation of resources to tasks but limits the size of problems that can be efficiently solved.

Although there are several software computer applications such as Microsoft project planner, suretrack, and other programs that <sup>can be used for</sup> do resource leveling, the last chapter of this report <sup>describes</sup> covered resource leveling using Primavera project planner since is it the software application that most project managers use <sup>today</sup> nowadays.

During the last two decades, the construction industry has progressed in this trend of improving resource allocation, not merely out of interest, but as a means of survival in a more competitive world. However, it is apparent that in the future, resource planning and resource allocation will still present considerable challenge <sup>and</sup> source <sup>of</sup> frustration to researchers in <sup>applied</sup> mathematics and operations research.

## REFERENCES

1. Clough, Richard H. and Sears, Glenn A. , Construction Project Management, John Wiley & Sons, Inc., New York, 1991, pp. 157-158.
2. Westney, Richard E., Managing the Engineering and Construction of Small Projects, Marcel Decker, Inc., New York, 1985, p. 67.
3. Ritz, George J., Total Construction Project Management, McGraw-Hill, Inc., New York, 1993, p. 182
4. Ritz, op. cit. , p. 183
5. Ritz, op. cit. , p. 184
6. Ibid.
7. Ritz, op. cit. , p. 186
8. Ritz, op. cit. , pp. 185-188
9. Ibid. .
10. Ritz, op. cit. , p. 191
11. Ritz, op. cit. , p. 192
12. Ritz, op. cit. , p. 193-194
13. Ritz, op. cit. , p. 195
14. Ritz, op. cit. , p. 196
15. Ritz, op. cit. , p. 197
16. Carmichael, D. G. , Construction Engineering Networks, John Wiley & Sons, Inc., 1989, p. 65
17. Ibid. .
18. Carmichael, op. cit. , p. 66
19. Carmichael, op. cit. , p. 67

20. Carmichael, op. cit. , p. 66
21. Carmichael, op. cit. , p. 67
22. Carmichael, op. cit. , p. 69
23. Carmichael, op. cit. , p. 70
24. Carmichael, op. cit. , p. 71
25. Stevens, James D., Techniques for Construction Network Scheduling, McGraw-Hill, Inc., 1990, pp. 123-124
26. Ahuja, H. N. , Construction Performance Control by Networks, John Wiley & Sons, Inc. , 1976, pp. 241-242
27. Naylor, Henry, Construction Project Management, Delmar Publishers, 1995, pp. 145
28. Naylor, op. cit. , p. 148
29. Naylor, op. cit. , p. 156
30. Naylor, op. cit. , p. 157
31. Meredith, Jack R. and Samuel J. Mantel Jr., Project Management, John Wiley & Sons, Inc., Second Edition, 1989, p. 340
32. Meredith, op. cit. , p. 341
33. Meredith, op. cit. , p. 342
34. Meredith, op. cit. , p. 343
35. Meredith, op. cit. , p. 344
36. Meredith, op. cit. , pp. 348-349
37. Ahuja, op. cit. , pp.221-225
38. Ibid.
39. Ibid.
40. Fenley, L. G. , "Towards the development of a complete Multi-project Scheduling System", Journal of Industrial Engineering, Oct 1978

41. Microsoft, Primavera Project Planner, Primavera Systems, Inc., 1993, p. 120
42. Microsoft, op. cit. , p. 121
43. Ibid
44. Microsoft, op. cit. , p. 122
45. Microsoft, op. cit. , p. 123
46. Microsoft, op. cit. , p. 127
47. Microsoft, op. cit. , p. 129
48. Microsoft, op. cit. , p. 130
49. Microsoft, op. cit. , p. 133
50. Microsoft, op. cit. , pp. 136-137

## BIBLIOGRAPHY

- Adrian, James J. , CM: The Construction Management Process, Reston Publishing Company, Inc. , 1981, pp. 169-206
- Adrian, James J. , Construction Productivity Improvement, Elsevier Science Publishing Co., Inc., 1987, pp. 211-257
- Adrian, James J. , Microcomputers in the Construction Industry, Prentice Hall Company, 1985, pp. 178-228
- Ahuja, H. N., Construction Performance Control by Networks, John Wiley & Sons, Inc. , 1976, pp. 201-298
- Carmichael, D. G. , Construction Engineering Networks, John Wiley & Sons, Inc., 1989, pp. 65-97
- Clough, Richard H. and Glenn A. Sears, Construction Project Management, John Wiley & Sons, Inc., Third Edition, 1991, pp. 157-179
- Frankel, Ernst G., Project Management in Engineering Services and Development, Butterworth & Co. (Publishers) Ltd., 1990, pp. 36-39
- Hendrickson, Chris and Tung Au, Project Management for Construction, Prentice Hall, 1989, pp. 297-335
- Halpin, Daniel W. and Ronald W. Woodhead, Construction Management, John Wiley & Sons, Inc., 1980, pp. 313-335
- Meredith, Jack R. and Samuel J. Mantel Jr., Project Management, John Wiley & Sons, Inc., Second Edition, 1989, pp. 327-354
- Microsoft, Primavera Project Planner, Primavera Systems, Inc., 1993, pp.119-138
- Naylor, Henry, Construction Project Management, Delmar Publishers, 1995, pp. 121-160
- Nunally, S. W. , Construction Methods and Management, Regents/Prentice Hall, 1993, pp. 361-385
- O'Brien, James, CPM in Construction Management, McGraw Hill, Inc., Second Edition, 1971, pp. 190-217



Popescu, Calin M., Project Planning, Scheduling, and control in Construction, John Wiley & Sons, Inc., 1995, pp. 51-73

Ritz, George J., Total Construction Project Management, McGraw-Hill, Inc., 1994, pp. 181-199

Stevens, James D., Techniques for Construction Network Scheduling, McGraw-Hill, Inc., 1990, pp. 123-141

Westney, Richard E., Managing the engineering and Construction of Small Projects, Marcel Decker, Inc., 1985, pp. 197-218

Willis, Edward, Scheduling Construction Projects, John Wiley & Sons, Inc., 1986, pp. 321-337.